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NOTE: Still photographs and video are available to accompany this release. Call the Ames Media Services Office at (415) 604-9000.

MOUNTAIN VIEW, Calif. -- NASA scientists will use "telepresence technology" to study Antarctic lakes this fall to learn more about life forms which once may have existed on Mars.

A five-member research team will travel to Antarctica in October to study sediment on the bottom of ice-covered Lake Hoare on Ross Island. They will examine the physical and biological nature of the lake, including its temperature, chemical composition and the gas content of the water. The key research tool will be a mini-submarine mounting a camera that researchers will control with a video headset.

- more -

"Antarctica is the most Mars-like environment on Earth," said Dr. Carol Stoker, a NASA Ames Research Center scientist and expedition team member. "We're taking this technology to a hostile environment to conduct research that has direct applications to NASA's goal of exploring Mars."

The team also plans to continue studies of ice-covered lakes started earlier this year during a joint NASA-Russian expedition in the Bunger Hills Oasis of Eastern Antarctica. That study was part of Ames' research into microbes living in extreme environments.

The telepresence technology relies on a video headset that lets researchers use head movements to point the camera on the underwater vehicle. Team members will steer the vehicle by remote control with joysticks or body motion.

"There is lots of work going on in the Silicon Valley using telepresence in various engineering applications," Stoker said. "But we are the only ones using this technology for field science."

The two-month expedition is a joint NASA-National Science Foundation project. Team leader is Dr. Robert Wharton, a scientist from the Desert Research Institute at the University of Nevada. Other team members are Dr. Scott Tyler of the Desert Research Institute and two Ames researchers, Stoker, Dale Andersen and Don Barch.

The Telepresence-Controlled Remotely Operated Vehicle was built by Deep Ocean Engineering Inc., San Leandro, Calif.

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NASA Facts

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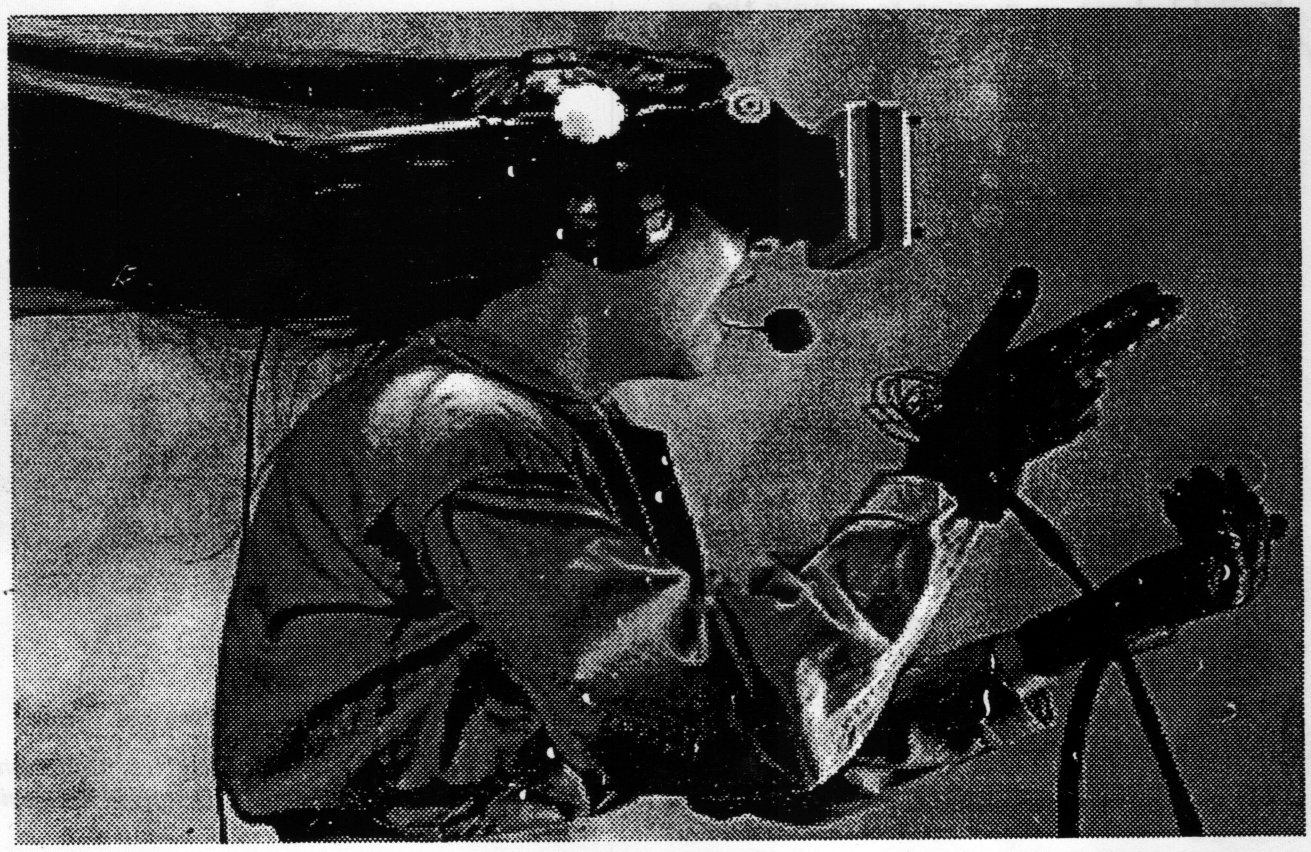
Space Administration

NASA SPACE TECHNOLOGY: VIRTUAL REALITY



Virtual reality lets people interact with a computer-generated "world" as if it were real

Strap on a set of computerized goggles and you are instantly on the far-off surface of Mars. As you look right and left the rocky, rust-red terrain stretches to the horizon. You pick up a Martian rock; a special glove lets you feel its texture and weight, just as if you were really there. . . .

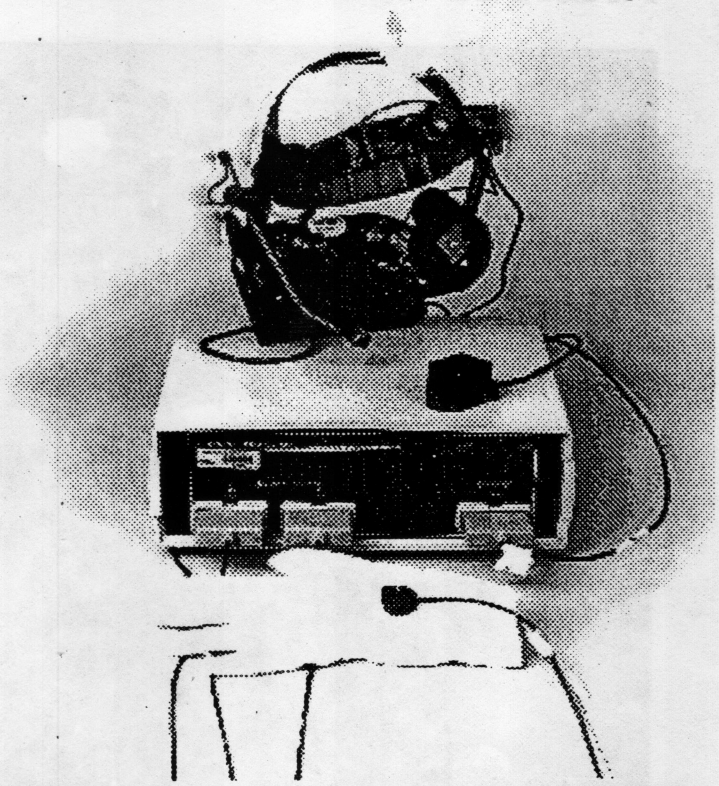
NASA is putting this concept of "virtual reality"—interacting naturally with a 3-D computer-generated world—to use in its space and aeronautics missions. For example, virtual reality will let scientists plan the best routes for robots and humans to explore the surface of the Moon and Mars. Astronauts can try out space repair tasks and perfect their skills before they lift off. Researchers can see the flow of air over an airplane or spacecraft from any angle, or take a realistic trip into the heart of a cosmic "black hole."

Many experts feel that virtual reality is the ideal way for people to work with computers. The standard setup of keyboard, video screen and "mouse" uses only a fraction of our human senses. In a well-designed virtual system, a person moves and acts within the environment in a natural, more effective manner.

A virtual system has several integrated parts. There is always a computerized description ("database") of the setting to be studied or manipulated. It can be a physical place, such as a planet's surface made from digitized images sent back by space probes. It may be more abstract: ozone levels at various heights in Earth's atmosphere or a "menu" hanging in mid-air from which computer commands can be selected.

Virtual systems also use a special helmet or goggles to supply the sights and sounds of the synthetic environment. Video displays are coordinated to produce a three-dimensional effect, like high-tech 3-D movie glasses. Headphones make sounds seem to come from any direction. Special sensors track head motions so that the visual and audio images shift in response.

Most systems also include a glove with special electronic sensors; the glove lets a user interact with the virtual world through hand gestures. He or she can move or touch objects in the visual display and they respond just as they would in the physical world. Advanced versions of the glove also provide artificial sensations so that an item feels like and has the weight of the real thing.



A typical virtual system: stereo video goggles, headphones, a glove with special sensors and a motion tracking device

Developing The Technology

Virtual reality is still very new. Most of the video displays need more convincing detail and the field of view is unnaturally restricted. Scene changes lag behind the user's head movements because the position trackers have limitations and computer speed is not yet fast enough to keep up.

NASA is studying ways to improve virtual systems with a prototype multi-sensory virtual workstation at Ames Research Center, Mountain View, Calif. The workstation has a custom-built, head-mounted stereo video display, fiberoptic gloves and magnetic motion trackers. It recognizes voice commands and can talk in its own electronic speech.

Much of the virtual research at Ames tries to answer a basic question: What is required to make a virtual system match the ways we sense the real world? The studies look at issues such as how the eyes and brain track objects in three dimensions, the interaction between the eyes and position-sensing organs in the ear and better ways to send realistic force and torque feedback when an object is moved.

Sound is also a vital channel of information, so NASA is testing a system that gives 3-D auditory cues through a pair of headphone speakers. The system is based on computer models of the manner in which the outer ear hears sounds at various distances and directions. It makes voices, warning alarms and other sounds seem spatially located and can simulate as many as four moving or stationary audio sources.

Better knowledge of the human factors that relate to the virtual world, coupled with computer hardware and software advances, will let NASA build virtual systems that have more realistic displays, faster response times and lower cost. Virtual technology will then be ready to serve its main purpose: helping NASA meet its aeronautics and space goals in the 21st century.

The Next Best Thing To Being There

Scientists have often used pictures sent back by U.S. spacecraft to create a sense of being on or near another planet. In the mid-1960s, for example, they made photo-mosaics of Surveyor lunar landing sites by pasting images inside spherical shells to "see" the moon from the lander's point of view. More recently, computerized flyovers of Earth, Mars, Venus and Uranus's moon Miranda have been created using digital data from robotic explorers.

NASA is taking that approach a step further with the Visualization for Planetary Exploration program. The program, based at Ames Research Center, focuses on developing virtual reality systems that could help humans and robots explore the moon, Mars and other bodies in the solar system.

As a first step, the Visualization for Planetary Exploration staff is interviewing leading planetary geologists about how they work in the field and how they visualize terrain data. NASA researchers also have examined the methods used by geological site experts at the Amboy lava field in California's Mojave Desert and at Hualalai volcano on the island of Hawaii.

The Ames scientists are using that knowledge to help develop and evaluate human interaction with a virtual exploration system. The prime research tool is a computer graphics testbed based on virtual workstation technology. Much of the work uses digital images returned by the Viking probes that landed on Mars in 1976.

Novel computing techniques lets users to examine a planetary surface in varying degrees of detail, depending on what they want to do. With a feature called "virtual pixel mapping," for example, the system can show a panorama of the Viking landing site—or any area for which NASA has detailed digital terrain data—with realistic color, sun illumination and surface texture. The system "pre-computes" what the terrain will look like if the user turns or looks up and down, so there is no lag between head movements and scene changes.

If a user wants to move from place to place on the virtual Martian surface, the computer can restrict the complexity of the scene during rapid motions. When he or she stops for a closer look, the detail increases dramatically. This approach has a drawback:

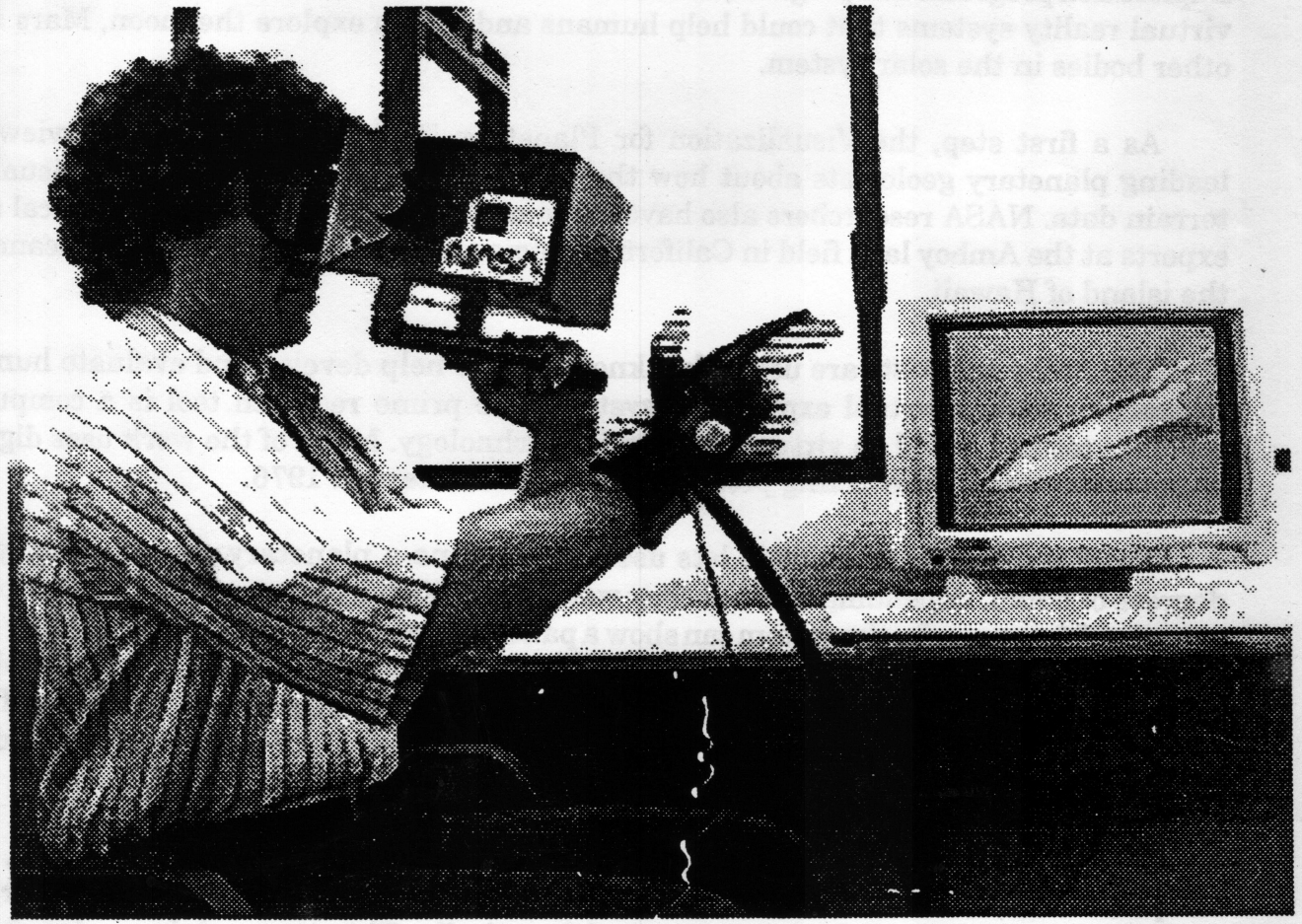
the simplified "cartoon" Mars scenes are relatively crude and landmarks become unrecognizable during movement. Researchers are working to compute views that retain the essential features of the terrain without losing the ability to move through it at normal speed.

The first practical use of virtual technology in a planetary mission may come soon. A NASA geologist proposes to use the system to study surface data sent back by the Mars Observer spacecraft, which is slated to orbit the Red Planet starting in August 1993.

From Wind Tunnels to Black Holes

A virtual world does not have to be a physical place. It can be a computer-generated display of anything a researcher wants to examine or experiment with—ozone layers in the atmosphere, air streaming around an object, even the bizarre environment around a cosmic "black hole."

Seeing physical phenomena in three dimensions has special advantages for engineers because new aircraft and spacecraft designs depend heavily on visual testing methods such as wind tunnel trials and computer studies to make sure they work as intended. At Ames Research Center, NASA scientists have developed a "virtual wind tunnel" that combines the advantages of these traditional methods to solve real engineering problems.



A NASA researcher demonstrates virtual wind tunnel technology at Ames Research Center

The virtual tunnel uses a boom-mounted viewer that creates an illusion of depth with coordinated stereo images, much like the virtual workstation helmet. The system tracks head motions and moves the point of view accordingly, letting a user see airflow over an object from anywhere inside or outside the airstream. An advanced glove with position and finger joint sensors allows various tracers (e.g., smoke) to be injected into the virtual airflow so that its path over the object can be seen.

Although virtual wind tunnel technology is still in a test and research phase, its benefits are becoming clear. Perhaps its biggest edge is that engineers can interact with their experiments in a natual manner, allowing them to focus on the real-time results of the test run. They can freeze the scene at any point to "walk around" inside the airflow and note any design problems or unusual phenomena they may want to study in greater detail and from any angle.

Virtual systems could also be used to animate complex data bases of information important to NASA's science and technology missions. Scientists cannot see the magnetic fields around Earth or the incredible gravity forces in a far-off black hole, but they do have measurements on the effects these phenomena have on their surroundings. Researchers are working on methods to create virtual simulations of such normally invisible celestial objects and learning how studying and manipulating them in 3-D can add to our scientific knowledge.

Sound Information

Virtual reality relies heavily on visual displays. But NASA researchers are finding out that virtual 3-D sounds presented through earphones can be an excellent way to convey warnings and other information to pilots flying in the world's increasingly-crowded airways. At Ames Research Center, virtual audio technology is being used to study systems that could let pilots and air traffic controllers monitor three-dimensional situations more easily and safely with either voice transmissions or coded sounds, such as a beep.

For example, the Traffic Collision Avoidance System (TCAS) now installed in all commercial airliners alerts pilots that another plane is close, but crew members must look for and find the other aircraft. Tests in a NASA simulator linked the out-the-window position of another airplane with the virtual position of the word "traffic" heard through headphones. In the experiments, pilots saw the other simulated aircraft an average 2.5 seconds sooner when warnings were sounded through virtual headphones compared to alerts through a single earpiece.

In normal air-to-ground communications, a 3-D sound system can place concurrent radio conversations in separate virtual positions around a crew member. Messages could come from the front, rear, side or an intermediate location. A virtual system makes messages sound clearer against background noise and can make them more intelligible in situations where pilots must monitor several radio frequencies, such as near an airport.

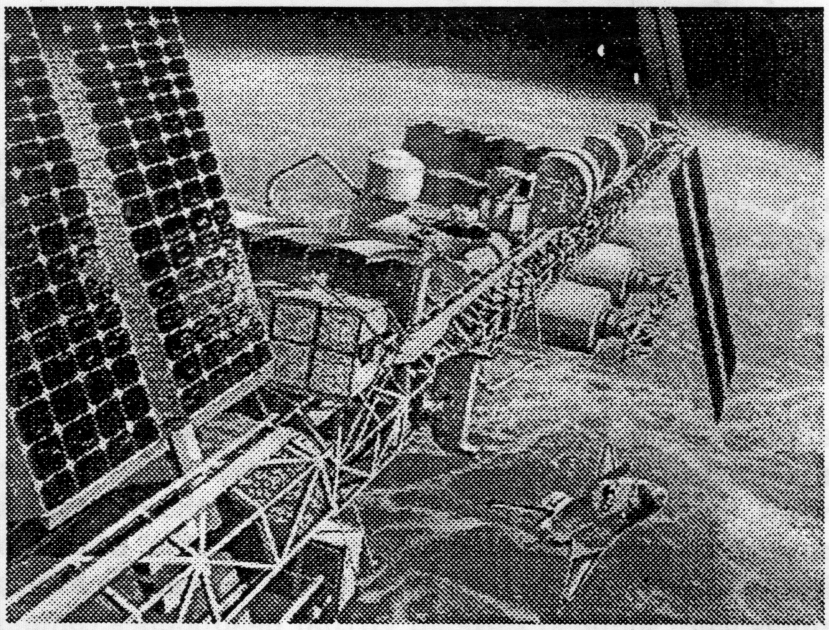
Virtual audio technology may eventually help air traffic controllers in the same way. Radio messages would be virtually located in controllers' headphones to sort transmissions by aircraft direction, altitude or message purpose.

Training For Tomorrow's Missions

As virtual technology improves, NASA is finding new ways to use it in its space and aeronautics efforts. Because a person is immersed in a computerized world where any mission situation can be copied or imagined, many experts believe virtual reality can become a highly effective training tool possible for pilots and astronauts.

For example, crew members could "fly" in a new cockpit or perfect spacewalking tasks without leaving the ground. Specialists could learn to operate scientific instruments in a virtual environment before the devices are built or flown. Under controlled, realistic conditions, astronauts will be able to practice flying and working next to large objects while circling Earth at 17, 500 miles per hour.

NASA's Johnson Space Center, Houston, is actively pursuing several projects that would use virtual technology in training exercises such as simulations of Space Shuttle extravehicular activity, Space Station Freedom operations and maintenance flights to the orbiting Hubble Space Telescope. Mission managers and astronauts can plan, analyze and modify work techniques to ensure a successful and productive flight without the need to use large, expensive training facilities.



Virtual reality could eventually be the ultimate training tool for astronauts manuevering around and docking with large space structures such as Space Station Freedom

Johnson researchers are also working with NASA's Marshall Space Flight Center, Huntsville, Ala., to let people at both centers simultaneously share the same virtual environment. This innovative use of virtual technology would eliminate complications when the two centers do joint training activities such as for Spacelab scientific missions, which are controlled from both Houston and Huntsville.

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Telepresence for the Exploration of Hostile and Remote Environments: From Sea to Space

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Abstract

Telepresence will enable a significant extension of human capabilities in many different situations ranging from scientific exploration of remote and hazardous environments on Earth to the exploration of distant worlds. Telepresence is a high fidelity form of remote control in which the natural sensory capabilities of the human operator (e.g vision, touch) are projected into a robot at a distant work site. We have developed a telepresence interface to a Remotely Operated underwater Vehicle (ROV). The ROV is an off the shelf teleoperated S2 phantom built by Deep Ocean Engineering of San Leandro, CA. Telepresence is being incorporated onto the vehicle via an underwater camera, the pointing of which is servo-controlled by head motions of an operator. Images from stereo camera's on the underwater vehicle are projected onto a head mounted display of the type used in Virtual Reality work. Telepresence systems are designed to make the operator "feel present" in the remote environment by providing sensory feedbackand spatial correspondance of vision. The Telepresence-controlled ROV (TROV) is being used to conduct scientific study of underwater environments including a coral reef ecosystem and the exploration of permanently ice-covered Antarctic lakes. By using telepresence technology to do field science, these expeditions will provide insight about how the projection of human senses to a remote location can improve or expedite the scientific return. In addition to scientific returns that this work will provide, there will also be insights into how telepresence can be used for a variety of tasks ranging from exploration to construction.

From Proceedings of IDEAA 1: International Conference on Design for Extreme Environments, Nov.5-10, 1991, Houston TX

Introduction

As part of President Bush's Space Exploration Initiative (SEI), the National Aeronautics and Space Administration (NASA) is developing the technology that will be necessary for future robotic and human exploration of the moon and the planet Mars. These exploration efforts will require the synergistic efforts of humans and machines. Teleoperated robotic vehicles will, in all likelihood, fulfill much of this need; however this capability has yet to be demonstrated in a realistic setting. Thus, "telepresence" systems to support scientific field work in the marine environment are being developed at NASA's Ames Research Center. Telepresence is a high fidelity form of remote control in which the natural sensory capabilities of the human operator (e.g vision, touch) are projected into a robot at a distant work site. Telepresence systems are being integrated with underwater remotely operated vehicles that are available today on the commercial market. The union of "off-the-shelf" technology with "state-of-the-art" telepresence systems could enhance the capabilities of these underwater vehicles for exploratory work.

Using telepresence-controlled remote exploration vehicles has been proposed as a method of enhancing the capabilities of and expanding the land area that can be explored by astronauts on the moon (Spudis and Taylor, 1990) and Mars (Stoker *et al.*, 1989, 1990). Even in an extensive program of human exploration of the moon and Mars, people will only be able to directly access areas of a few kilometers in size because life support and safety requirements limit the amount of time humans can spend out on the planetary surface. This range limitation is in stark contrast to the scale of the regions to be explored. For example, one-way trip time to Mars for a human crew is 6-9 months and the possible territory to explore (the surface of Mars) has a land area equivalent to that of the Earth. Thus, technology to enhance the range of access is of high priority to enhance the scientific return of these missions.

Exploration of a planetary surface is analogous in many ways to operations in the undersea environment. Extra-vehicular activity from a spacecraft is conceptually similar to SCUBA diving where air supply and saturation depth range limit the distances and time that divers can spend underwater. As in space, the use of telepresence and teleoperation of remote vehicles has the potential to extend the range and capabilities of scientific activity that can be conducted in the submarine environments. Many scientific problems in the marine environment require similar capabilities for their study in the field to those that will be needed for geologic exploration of a planetary surface. These similarities include having the ability to navigate to an object in a known location, having the ability to collect samples requiring a high degree of dexterity, and having the ability to examine features a few milimeters in size.

From a technological standpoint, using telepresence technology to study submarine environments will provide scientists and engineers with the opportunity to work with telepresent control of remote vehicles for the first time in an environment other than the laboratory bench-top. The development of such technology requires actual use by scientists during the collection of scientific data. This work could lead to a revolutionary way of conducting science in hostile or remote environments on Earth and will

provide a useful operational background for using this technology in the future exploration of other planetary bodies.

From a scientific standpoint, telepresence technology could greatly enhance and expand the abilities of scientists to conduct scientific field work underwater. Conventional approaches, primarily the use of divers on SCUBA and submersibles, are limited in terms of bottom-time (SCUBA), overall time constraints, and constraints on maneuverability (in the case of manned submersibles). In addition, underwater exploration, particularly using SCUBA, can be extremely hazardous.

TROV System Description

Description of TROV Concept

The TROV uses an S2 SuperPhantom™ (Deep Ocean Engineering) Remotely Operated Underwater Vehicle controlled by a "telepresent" operator. The TROV differs from standard ROV operation by using enhanced teleoperated control that is able to project the natural capabilities of the human operator to the ROV and provide him/her with a high degree of sensory feedback information. A telepresence interface to the Superphantom ROV has been developed in a collaboration between Deep Ocean Engineering and NASA Ames Research Center. An artist's depiction of an advanced TROV concept is shown in Figure 1. In this concept, manipulators on the underwater vehicle are operated by using data gloves. The vehicle steering is provided by a chair which translates the body motions of the operator into control signals to the TROV.

An important key to creating a sense of presence is being able to translate a sense of the 3-D remote operating space to the operator. In order to accomplish this, the visual display from the remote vehicle should be spatially correspondent to the orientation of the ROV. This is accomplished by mounting a two-axis-movable (Pan and Tilt) camera platform on the ROV and providing control inputs to this platform via a head-motion tracker mounted on the operator's head. Thus, motions of the operator's head control the pointing of the underwater cameras.

Stereo Images from the underwater cameras are displayed on a visual system mounted in close proximity to the operator's eyes. We are testing a number of visual display systems for our application. In this regard, many such systems have been developed for use in Virtual Reality and military applications. The optimal system for this application should be color, wide field of view and should have high enough resolution to be able to display the full available video signal. The unit should be able to be worn comfortably and should put little weight on the operators head. The visual record is continuously recorded via VCR, and can be time-correlated with data records from other instruments mounted on the TROV. The video record which includes everything the user sees (and on a sound channel, everything that was said) can be replayed either on a standard Video/Television or through the headset. Thus, telepresence allows the possibility of recreating the experience of underwater vehicle operation after the fact.

The operator will also be able to control a multi-function manipulator mounted on the TROV. In evaluating the factors which support a feeling of physical

presence, visual and tactile senses are clearly of great importance. Less obvious, but equally important, is hearing. Tests of underwater manipulators have shown (Ballou *et al.*, 1985) that aural sense is highly linked with tactile sense in providing sensory information normally associated with touch. Using audio feedback, one can easily distinguish between materials, detect differences in surface textures, etc. Audio feedback also substitutes for force feedback in giving the user a sense of how much force the manipulator is applying to an object. Consequently, the manipulator system mounted on the TROV will be equipped with an audio feedback system.

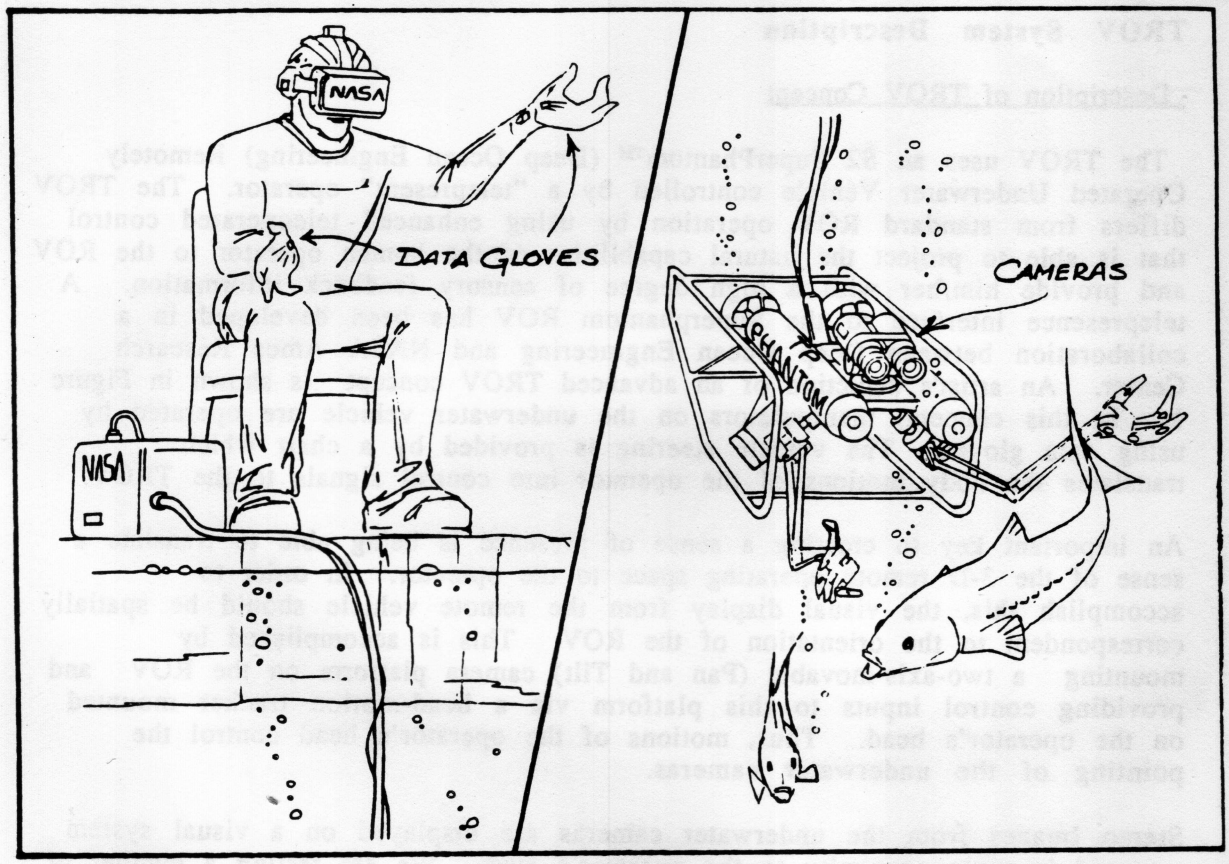

Figure 1: Telepresence is used to operate a TROV. Position of camera platform on the vehicle is articulated by head motions of an operator wearing a visual system that receives images from the underwater cameras. The manipulators on the vehicle are servo-controlled by the operator's hand motions using "data gloves".

Current Configuration of TROV

Figure 2 shows a photograph of our current TROV configuration. The Only the telepresent vision aspect of the TROV operation has been implemented so far. Our future plans call for developing servo-controlled manipulators for the vehicle which will be operated using data gloves and for developing a chair which will be used to control the vehicle's mobility (Figure 1). In this section, we discribe the system which has been developed and tested up to the present time.

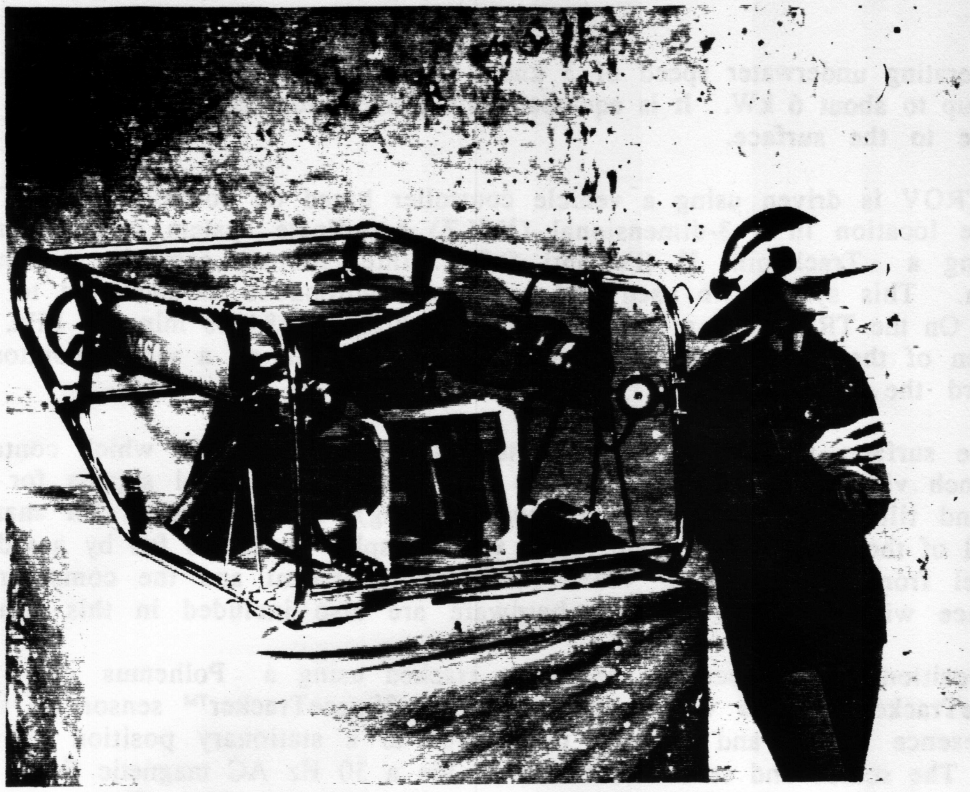

Figure 2. Photo of TROV and Helmet.

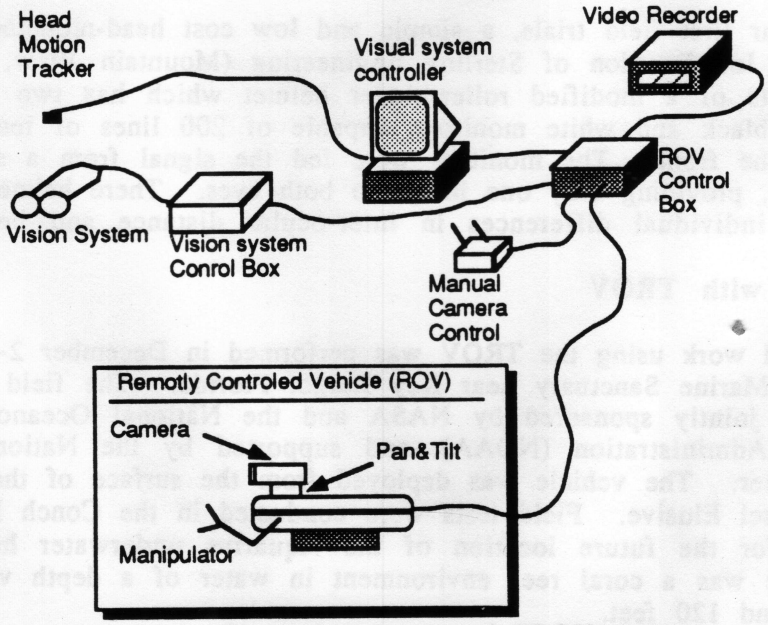

Figure 3. Conceptual layout of TROV system.

Figure 3 illustrates each of the major subsystems in our current TROV. The underwater vehicle is a SuperPhantom 2 capable of movement in four axes. This vehicle is pressure tested for 1500 feet (457.2 m) and carries two 250 watt tungsten-halogen lights with dimmers. It has a weight of 150 lbs (68 kg) and

an operating underwater speed of 3 knots (1.54 m/s). It uses either 115 or 230 VAC up to about 6 kW. It is equipped with a 1,100 foot cable to tether the vehicle to the surface.

The TROV is driven using a vehicle controller based on control-sticks. The vehicle location in a 3-dimensional (X,Y,Z) coordinate system is determined utilizing a Trackpoint II (Ferranti O.R.E. International) acoustic tracking system. This system we used had a surface hydrophone hardmounted to the boat. On the TROV was a MultiBeacon transmitting at 184 db min., 23 kHz. The position of the vehicle was displayed on a grid system on a video monitor onboard the boat.

On the surface, the vehicle is connected to a control console which contains a five inch video monitor. Attached to the console are control signals for the pan and tilt camera (obtained via head-tracking), and a joystick for manual control of the pan & tilt system. The visual display system is fed by a video channel from the console. Video recording equipment and the computer to interface with the head tracking hardware are also included in this console.

The position of the operators head was tracked using a Polhemus 3SpaceTracker™ This works by placing the 3SpaceTracker™ sensor on the telepresence helmet and affixing the source to a stationary position above the user. The source and sensor communicate via a 30 Hz AC magnetic field. This gives us X, Y and Z relative position and roll, pitch and yaw. These signals were fed into an Apple Macintosh portable computer which interpreted signals from the 3SpaceTracker™ and translated them into commands to operate the underwater pan and tilt camera platform.

For use in our first field trials, a simple and low cost head-mounted display was developed by Joe Deardon of Sterling Engineering (Mountain View, CA). This system consists of a modified roller-blader helmet which has two Sony HandyCam™ black and white monitors, capable of 200 lines of resolution, mounted on the front. The monitors were fed the signal from a single camera on the TROV, providing only one image to both eyes. There helmet can be adjusted for individual differences in inter-ocular distance and head size.

Field Work with TROV

The first field work using the TROV was performed in December 2-9, 1991 in the National Marine Sanctuary near Key Largo, Florida. The field phase of this program was jointly sponsored by NASA and the National Oceanographic and Atmospheric Administration (NOAA), and supported by the National Undersea Research Center. The vehicle was deployed from the surface of the 48 foot Research Vessel Elusive. Field tests were conducted in the Conch Reef area, a site chosen for the future location of the Aquarius underwater habitat. The field site was a coral reef environment in water of a depth varying between 70 and 120 feet.

The primary purpose of the field trip was to determine the capabilities of using the telepresence system to perform field science in a coral reef ecosystem. An additional objective was to determine whether or not the TROV could actually provide operators with a sense of "being present" in the remote environment, and whether this sense of presence offered any advantages for performing science.

During the field trip, ten people operated the TROV. Of these, half were professional underwater researchers and very experienced scuba divers, and the other half were relatively inexperienced or non-divers with a scientific or engineering background. All the users found that , while operating the TROV, they felt a strong sense of presence in the remote environment. The strong sense of presence occurred in spite of the fact that the visual system which was used offered only black and white images, and the resolution was relatively low.

The TROV was used to perform the reconnaissance of a deep coral reef ecosystem. Specific tasks included inspecting corals for evidence of disease and obtaining a video tape while performing transects of the ocean bottom in a 500 sq. meter area surrounding the site chosen for the future location of the Aquarius Habitat, a permanent underwater habitat. In addition to providing a scientific tool for this investigation, this *in-situ* demonstration of the TROV brought this new technology to the attention of a much broader science community. The experience and insight gained from this pilot study will be used to develop a more refined TROV system for use in planned future investigations in the marine environment.

The Telepresence project, and the TROV capability, has been selected for the first pilot demonstration project for the new NSF/NASA Antarctic Space Analog Program. The goal of this project, scheduled for the 1992 Austral Summer, is to perform an integrated demonstration of telepresence, advanced power systems, and satellite communications/data link in Antarctica. The TROV will be used to perform the detailed reconnaissance of a permanently ice-covered lake in Antarctica. The environments in these lakes are thought to be similar to lakes which existed on Mars in the ancient past. The use of the TROV will allow the lakes to be explored in a considerably more detail than has previously been possible. In a later phase of the project, it will be possible to control the TROV in Antarctica from a distant location using satellite telecommunications.

Conclusions

Using telepresence to operate remote vehicles could lead to a revolutionary way of conducting science in hostile or remote environments on Earth. Field work using telepresence will help to advance the technology which will enable significantly enhanced capabilities for the exploration of other planetary bodies. Using telepresence to explore the marine environment will provide near term scientific benefits while helping to provide scientific drivers for the development of new technologies that will be needed for telepresent exploration of the moon and Mars.

Acknowlegements

Support for the current phase of the TROV project has been provided by NASA with contributions from the Exobiology and Planetary Geology Program Offices. We are greatful for the strong support of Dr. John Rummel of NASA Headquarters. We wish to thank Dr. Laurie Richardson for scientific leadership as well as logistical and moral support during the first field trials of the TROV. TROV field trials in Key Largo Florida were supported by the National Undersea Research Center. We wish to thank Dr. Steven Miller and

Lance Horne of NURC, as well as the extremely helpful support staff of the NURC facility, for their assistance with the field testing.

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NATURE AND ORIGINS OF VIRTUAL ENVIRONMENTS: A BIBLIOGRAPHICAL ESSAY

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Abstract—Virtual environments presented via head-mounted, computer-driven displays provide a new media for communication. They may be analyzed by considering: (1) what may be meant by an environment; (2) what is meant by the process of virtualization; and (3) some aspects of human performance that constrain environmental design. Their origins are traced from previous work in vehicle simulation and multimedia research. Pointers are provided to key technical references, in the dispersed, archival literature, that are relevant to the development and evaluation of virtual-environment interface systems.

1. COMMUNICATION AND ENVIRONMENTS

1.1. *Virtual environments are media*

Virtual environments created through computer graphics are communications media.[1] Like other media, they have both physical and abstract components. Paper, for example, is a medium for communication. The paper is itself one possible physical embodiment of the abstraction of a two-dimensional surface onto which marks may be made.† The corresponding abstraction for head-coupled, virtual image, stereoscopic displays that synthesize a coordinated sensory experience is an environment. These so called "virtual reality" media have only recently caught the international public's imagination,[3–6] but they arise from continuous development in several technical and nontechnical areas during the past 25 years.

1.2. *Optimal design*

A well designed computer interface affords the user an efficient and effortless flow of information to and from the device with which he interacts. When users are given sufficient control over the pattern of this interaction, they themselves can evolve efficient interaction strategies that match the coding of their communications to the characteristics of their communication channel.[7–10] But successful interface design should strive to reduce this adaptation period by analysis of the user's task and performance limitations. This analysis requires understanding of the operative design metaphor for the interface in question.

The dominant interaction metaphor for the computer interface changed in the 1980s. Modern graphical interfaces, like those first developed at Xerox PARC[11] and used for the Apple Macintosh (Fig. 1), have transformed the "conversational" interaction from one in which users "talked" to their computers to one which they "acted out" their commands in a "desk-top" display. This so called desk-top metaphor provides the users with an illusion of an environment in which they enact wishes by manipulating symbols on a computer screen.

1.3. *Extensions of the desk-top metaphor*

Virtual environment displays represent three-dimensional generalization of the two-dimensional "desk-top" metaphor.‡ These synthetic environments may be experienced either from egocentric or exocentric viewpoints. That is to say, the users may appear to actually be in the environment or see themselves represented as a "You are here" symbol[14] which they can control.

The objects in this synthetic universe, as well as the space itself within which they exist, may be programmed to have arbitrary properties. However, the successful extension of the desk-top metaphor to a full "environment" requires an understanding of the necessary limits to programmer creativity in order to insure that the environment is comprehensible and usable. These limits derive from human experience in real environments and illustrate a major connection between work in telerobotics and virtual environments. For reasons of simulation fidelity, previous telerobotic and aircraft simulations, which have many of the aspects of virtual environments, have had to explicitly take into account real-world kinematic and

† As described by James Hollan at the Panel on Virtual Reality, Western Communications Forum Panel 1991, Phoenix, Arizona, some new computer interfaces may resemble handwriting-recognizing magic slates on which users write commands with a stylus. See Ref. 2.

‡ Higher dimensional displays have also been described. See Ref. 12 and 13 for alternative approaches.

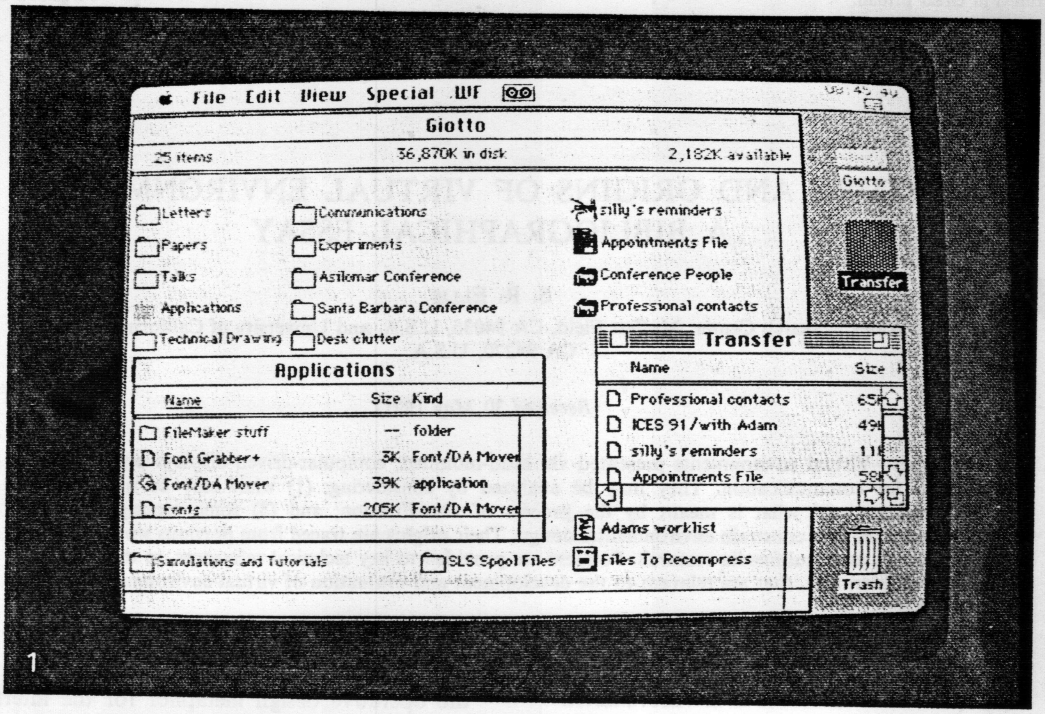


Fig. 1. Macintosh® screen display illustrating graphical icons with which the user interacts to control the computer's operating system. This mode of acting out commands was initially developed at Xerox PARC.

dynamic constraints in ways now usefully studied by the designers of totally synthetic environments.[15–19]

1.4. *Environments*

Successful synthesis of an environment requires some analysis of the parts that make up the environment. The theatre of human activity is an *environment* and may be considered to have three parts: a *content*, a *geometry*, and *dynamics*.[20]

1.4.1. *Content*. The *objects and actors* in the environment are its content. These objects may be described by *state vectors* which identify their position, orientation, velocity, and acceleration in the environmental space, as well as other distinguishing characteristics such as their color, texture, and energy. The state vector is thus a description of the *properties* of the objects. The subset of all the terms of the state vector which is common to every actor and object of the content may be called the *position vector*. Though the *actors* in an environment may, for some interactions, be considered objects, they are distinct from objects in that in addition to characteristics they have *capacities* to initiate interactions with other objects. The basis of these initiated interactions is the storage of energy or information within the actors, and their ability to control the release of this stored information or energy after a period of time. The *self* is a distinct actor in the environment which provides a *point of view* from which the environment may be constructed. All parts of the environment that are exterior to the self may be considered the field of action. As an example, the balls on a billiard table may be considered the content of the billiard table environment and the cue ball combined with the pool player maybe considered the "self".

1.4.2. *Geometry*. The geometry is a description of an environmental field of action. It has *dimensionality*, *metrics* and *extent*. The dimensionality refers to the number of independent descriptive terms needed to specify the position vector for every element of the environment. The metrics are systems of rules that may be applied to the position vector to establish an ordering of the contents and to establish the concept of geodesic or straight lines in the environmental space. The extent of the environment refers to the range of possible values for the elements of the position vector. The environmental space or field of action may be defined as the Cartesian product of all the elements of the position vector over their possible ranges. An environmental trajectory is a time-history of an object through the environmental space. Since kinematic constraints may preclude an object from traversing the space along some paths; these constraints are also part of the environment's geometric description.

1.4.3. *Dynamics*. The dynamics of an environment are the *rules of interaction* among its contents describing their behavior as they exchange energy or information. Typical examples of specific dynamical rules may be found in the differential equations of Newtonian dynamics describing the response of billiard balls to impacts initiated by the cue ball. For other

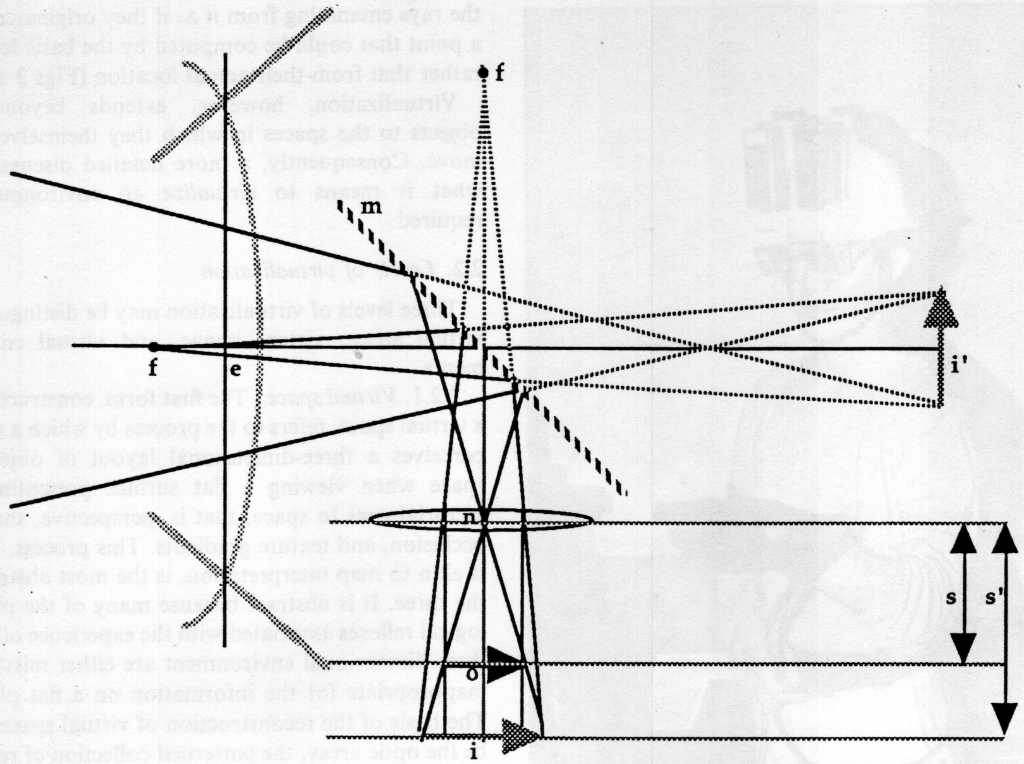


Fig. 2. Virtual image created by a simple lens with focal length f placed at n and viewed from e through a half-silvered mirror at m appears to be straight ahead of the viewer at i'. The visual direction and accommodation required to see the virtual image clearly are quite different than what would be needed to see the real object at o. An optical arrangement similar to this would be needed to superimpose synthetic computer imagery on a view of a real scene as in at heads up display.

environments, theses rules may also take the form of grammatical rules or even of look-up tables. For example, a syntactically correct command typed at a computer terminal can cause execution of a program with specific parameters. In this case the information in the command plays the role of the energy, and the resulting rate of change in the logical state of the device, plays the role of acceleration.†

1.5. *Sense of physical reality*

Our sense of physical reality is a construction from the symbolic, geometric, and dynamic information directly presented to our senses. It is noteworthy that many of the aspects of physical reality are only presented in incomplete, noisy form. We, for example, generally see only part of whole objects, yet through *a priori* knowledge that we bring to perceptual analysis, we know them to exist in their entirety.[21–23] Similarly, our goal seeking behavior appears to filter noise by benefiting from internal dynamical models of the objects we may track or control.[24,25] Accurate perception consequently involves considerable *a priori* knowledge about the possible structure of the world. This knowledge is under constant recalibration based on error feedback. The role of error feedback has been classically mathematically modeled during tracking behavior[26–28] and notably demonstrated in the behavioral plasticity of visual-motor coordination[29–31] and in vestibular reflexes.[32–34]

Thus, a large part of our sense of physical reality is a consequence of internal processing rather than being something that is developed only from the immediate sensory information we receive. Our sensory and cognitive interpretive systems are predisposed to process incoming information in ways that normally result in a correct interpretation of the external environment, and in some cases they may be said to actually "resonate" with specific patterns of input that are uniquely informative about our environment.[35–38]

These same constructive processes are triggered by the displays used to present virtual environments. However, in these cases the information is mediated through the display technology. The illusion of a enveloping environment depends on the extent to which all of these constructive processes are triggered. Accordingly, virtual environments can come in differ-

† This analogy suggests the possibility of developing an *informational mechanics* in which some measure of motion through the states of an information processing device may be related to the information content of the incoming messages. In such mechanics, the proportionality constant relating the change in motion to the message content might be considered the *informational mass* of the program.

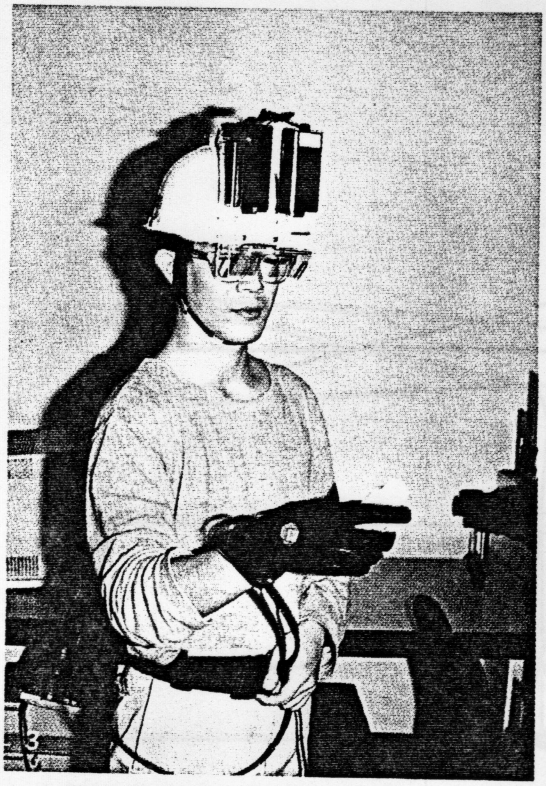


Fig. 3. See-through, head-mounted, virtual image, stereoscopic display that allows the user to interact with virtual objects synthesized by computer graphics which are superimposed in his field of vision.[39] The user's hand position is tracked electromagnetically and its shape is measured by the VPL DataGlove®. (Photograph courtesy of Michitaka Hirose.)

ent stages of completeness, which may be usefully distinguished.

2. VIRTUALIZATION

2.1. *Definition of virtualization*

Virtualization may be defined as *the process by which a human viewer interprets a patterned sensory impression to be an extended object in an environment other than that in which it physically exists*. A classical example would be that of a virtual image as defined in geometrical optics. A viewer of such an image sees the rays emanating from it as if they originated from a point that could be computed by the basic lens law rather that from their actual location (Figs 2 and 3).

Virtualization, however, extends beyond the objects to the spaces in which they themselves may move. Consequently, a more detailed discussion of what it means to *virtualize* an environment is required.

2.2. *Levels of virtualization*

Three levels of virtualization may be distinguished: virtual space, virtual image, and virtual environments.

2.2.1. *Virtual space*. The first form, construction of a virtual space, refers to the process by which a viewer perceives a three-dimensional layout of objects in space when viewing a flat surface presenting the pictorial cues to space, that is, perspective, shading, occlusion, and texture gradients. This process, which is akin to map interpretation, is the most abstract of the three. It is abstract because many of the physiological reflexes associated with the experience of a real three-dimensional environment are either missing or inappropriate for the information on a flat picture. The basis of the reconstruction of virtual space must be the optic array, the patterned collection of relative lines of sight to significant features in the image, that is, contours, vertices, lines, and textured regions. Since scaling does not affect the relative position of the features of the optic array, perceived size or scale is not intrinsically defined in a virtual space.

2.2.2. *Virtual image*. The second form of virtualization is the perception of a virtual image. In conformance with the use of this term in geometric optics, it is the perception of an object in depth in which accommodative,† vergence,‡ and (optionally) stereoscopic disparity§ cues are present, though not necessarily consistent.[40] Since, virtual images can incorporate stereoscopic and vergence cues, the actual perceptual scaling of the constructed space is not arbitrary but, somewhat surprisingly, not simply related to viewing geometry.[41–43]

2.2.3. *Virtual environment*. The final form is the virtualization of an environment. In this case the key added sources of information are observer-slaved motion parallax, depth-of-focus variation, and wide field-of-view without a prominent frame. If properly implemented, these additional features can be consistently synthesized to provide stimulation of major physiological reflexes such as accommodative vergence,‖ vergence accommodation,¶ the optokinetic reflex,†† and the vestibular-ocular reflex.‡‡[44–45] These features when embellished by synthesized sound sources[46–50] can substantially contribute to an illusion of telepresence, that is, actually being present in the synthetic environment.

The fact that actors in virtual environments interact with objects and the environment by hand, head, and eye movements, tightly restricts the subjective scaling of the space so that all system gains must be

† Focusing required of the eye to make a sharp image on the retina.

‡ Convergence or divergence of the eyes to produce an apparently single image.

§ The binocular disparity to a point in space is the difference of the binocular parallax of that point measured from both eyes.

‖ Reflexive changes in the convergence of the eyes triggered by changes in the required focus.

¶ Reflexive changes in the focusing of the eye triggered by change in convergence.

†† Reflexive tracking eye movements triggered by movement of objects subtending large visual angles.

‡‡ Tracking eye movements triggered by vestibular stimulation normally associated with head or body movement.

carefully set. Mismatch in the gains or position measurement offsets will degrade performance by introducing unnatural visual-motor and visual-vestibular correlations. In the absence of significant time lags, humans can adapt to these unnatural correlations. However, time lags do interfere with complete visual-motor adaptation,[31,32] and when present in the imaging system can cause motion sickness.[51]

2.3. *Environmental viewpoints and controlled elements*

Virtual spaces, images or environments may be experienced from two kinds of viewpoints: egocentric viewpoints, in which the sensory environment is constructed from the viewpoint actually assumed by the user, and exocentric viewpoints in which the environment is viewed from a position other than that where the user is represented to be. In this case, the user can literally see a representation of himself. This distinction in frames of reference results in a fundamental difference in movements a user must make to track a visually referenced target. Egocentric viewpoints require compensatory tracking, and exocentric viewpoints require pursuit tracking. This distinction also corresponds to the difference between inside-out and outside-in frames of reference in the aircraft simulation literature. The substantial literature on relative human tracking performance in these alternative reference frames, and the general literature on human manual performance, may be useful in the design of synthetic environments.[52–53]

3. ORIGINS OF VIRTUAL ENVIRONMENTS

3.1. *Early visionaries*

The intuitive appeal that virtual environment technology obviously has is probably rooted in the human fascination with vicarious experiences in imagined environments. In this respect, virtual environments may be thought of as originating with the earliest human cave art,[54] though Lewis Carroll's *Through the Looking-Glass* certainly is a more modern example of this fascination.

Fascination with alternative, synthetic realities has been continued in more contemporary literature. Aldous Huxley's "feelies" in *Brave New World* were certainly a kind of virtual environment, a cinema with sensory experience extended beyond sight and sound. A similar fascination must account for the popularity of microcomputer role playing adventure games such as *Wizzardry*. Motion pictures, and especially stereoscopic movies, of course, also provide examples of noninteractive spaces.[55]

The contemporary interest in imagined environments has been particularly stimulated by the advent of sophisticated, relatively inexpensive, interactive techniques allowing the inhabitants of these environments to move about and manually interact with computer graphics objects in three-dimensional space. This kind of environment was envisioned in the science fiction plots of the movie *TRON* and William Gibson's 1985 *Neuromancer*, yet the first actual synthesis of such a system using a head-mounted stereo display was made possible much earlier in the middle 1960s by Ivan Sutherland who developed special-purpose fast graphics hardware.[56,57]

Another early synthesis of a synthetic, interactive environment was implemented by Myron Krueger[58–60] in the 1970s. Unlike the device developed for Sutherland, Krueger's environment was projected onto a wall-sized screen. In Krueger's VIDEOPLACE, the user's image appears in a two-dimensional graphic video world created by a computer. The VIDEOPLACE computer analyzed video images to deter-

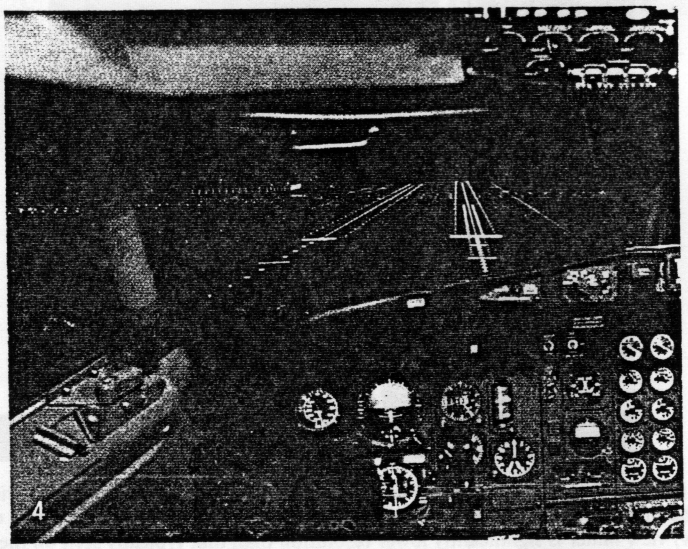


Fig. 4. View through the cockpit of a 727 simulator at the Ames Research Center which is used for human factors research. A simulated night flying environment is visible out the forward cockpit window. (Photograph courtesy of NASA.)

Fig. 5. This head-mounted, stereo, virtual environment display system at the Ames Research Center Advanced Display and Spatial Perception Laboratory is being used to control a remote PUMA robot in the Ames Robotics Laboratory. The simulation update rate varies from 12 to 30 Hz, depending on the complexity of the graphics. A local kinematic simulation of the remote work site aids the operator in planning complex movements and visualizing kinematic and operational constraints on the motion of the end effector. (Photography courtesy of NASA.)

mine when an object was touched by an inhabitant, and it could then generate a graphic or auditory response. One advantage of this kind of environment is that the remote video-based position measurement does not encumber the user with position sensors.

3.2. *Vehicle simulation and three-dimensional cartography*

Probably the most important source of virtual environment technology comes from previous work in fields associated with the development of realistic vehicle simulators, primarily for aircraft (see Refs 61 and 62; and Fig. 4), but also automobiles[63] and ships.[64,65] The inherent difficulties in controlling the actual vehicles often require that operators be highly trained. Since acquiring this training on the vehicles themselves could be dangerous or expensive, simulation systems synthesize the content, geometry, and

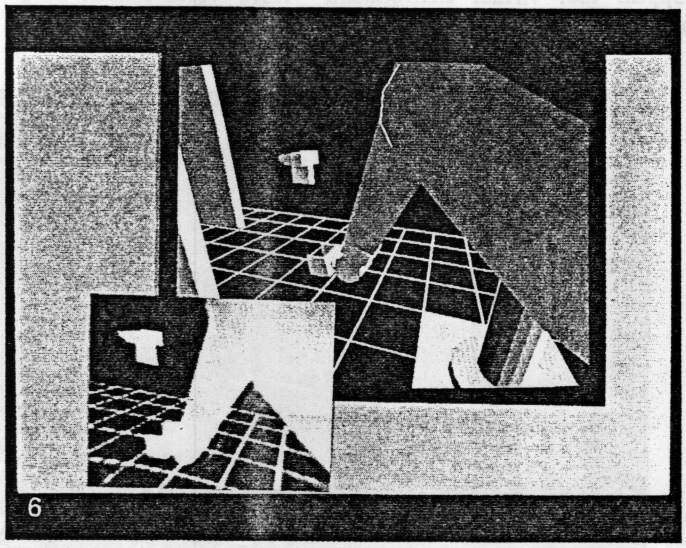


Fig. 6. As in all current relatively inexpensive, head-mounted virtual environment viewing systems, the view that the operator actually sees through the wide field (lower inset shows a part of the user's actual field of view) view finder is significantly lower resolution than that typically seen on the graphics monitors (background matched in magnification). The horizontal pixel resolution through view finder is about 22 arcmin/pixel, vertical resolution is 24 arcmin/line. Approximately 2 arcmin/pixel are required to present resolution at the center of the visual field comparable to that seen on a standard Macintosh monochrome display viewed at 57 cm. (Photograph courtesy of NASA.)

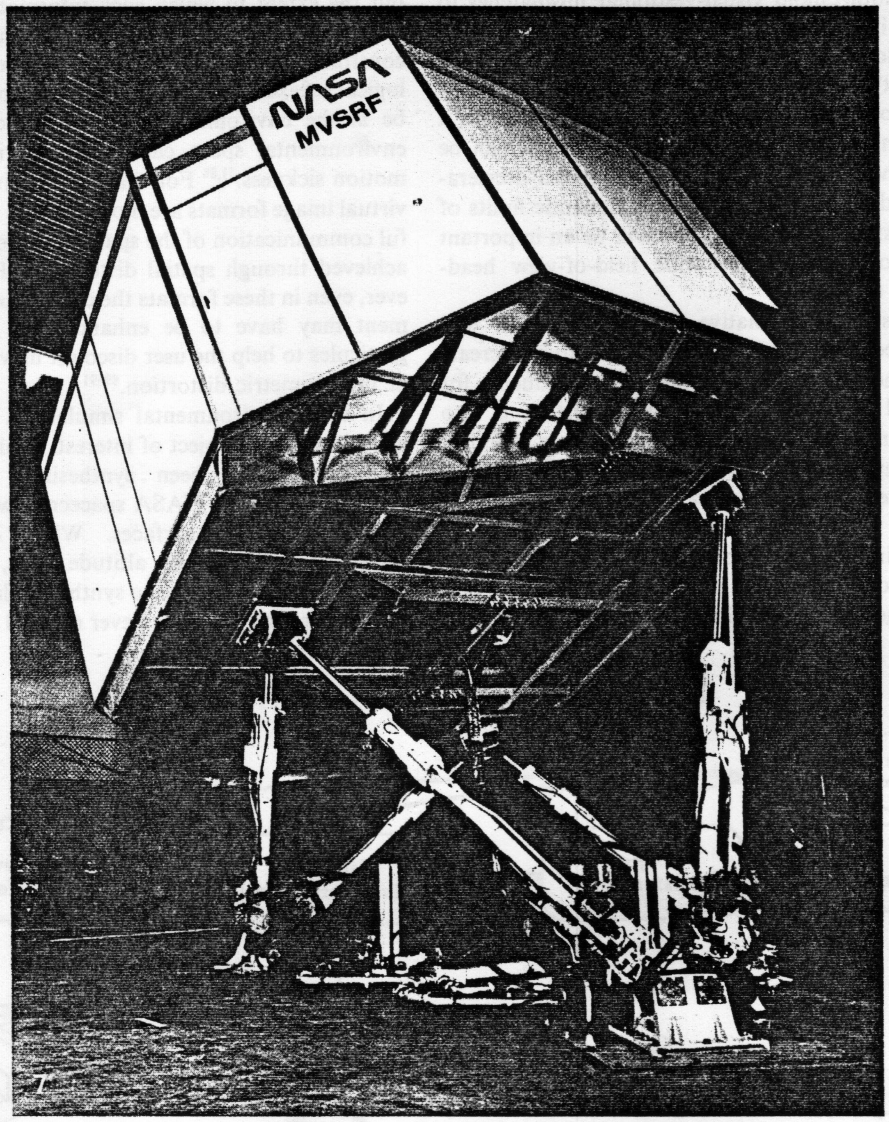


Fig. 7. Moving base simulator of the Aerospace Human Factors Division of Ames Research Center pitched so as to simulate an acceleration. (Photograph courtesy of NASA.)

dynamics of the control environment for training and for testing of new technology and procedures.

These systems have usually cost millions of dollars and have recently involved helmet-mounted displays to recreate part of the environment.[66–69] Declining costs have now brought the cost of a virtual environment display down to that of an expensive workstation and made possible "personal simulators" for everyday use (see Refs 70 and 71; and Figs 5 and 6).

The simulator's interactive visual displays are made by computer graphics hardware and algorithms. Development of special-purpose hardware, such as matrix multiplication devices, was an essential step that enabled generation of real-time, that is, greater than 20 Hz, interactive three-dimensional graphics.[56,57,72] A recent example is the "geometry engine" in Silicon Graphics IRIS workstations.[73,74] It enhances processing of the viewing transformation. These "graphics engines" can project hundreds of thousands of Gouraud shaded polygons per second.[75] Though this number may seem large, rendering of naturalistic objects and surfaces can require from 10,000 to 500,000 polygons. Software techniques are also important for improved three-dimensional graphics performance. "Oct-tree" data structures, for example, have been shown to dramatically improve processing speed for inherently volumetric structures.[76,77]

Since vehicle simulation may involve moving-base simulators, programming the appropriate correlation between visual and vestibular simulation is crucial for a complete simulation of an environment (Fig. 7). Moreover, failure to match these two stimuli correctly can lead to motion sickness.[78] Paradoxically, however, since the effective travel of most moving base simulators is limited, designers must learn how

to use subthreshold visual-vestibular mismatches to produce illusions of greater freedom of movement. These allowable mismatches are built into so-called "washout" models[16,79] and are key elements for creating illusions of extended movement. For example, a slowly implemented pitch-up of a simulator can be used to help create an illusion of forward acceleration. Understanding the tolerable dynamic limits of visual-vestibular miscorrelation will be an important design consideration for wide field-of-view head-mounted displays.

The use of informative distortion is also well established in cartography[80] and is used to help create a convincing three-dimensional environment for simulated vehicles. Cartographic distortion is also obvious in global maps which must warp a spherical surface into a plane[81,82] and three-dimensional maps, which often use significant vertical scale exaggeration (6–20×) to clearly present topographic features. Explicit informative geometric distortion is sometimes incorporated into maps and cartograms presenting geographically indexed statistical data,[83–87] but the extent to which such informative distortion may be incorporated into simulated environments is constrained by the user's movement-related physiological reflexes. If the viewer is constrained to actually be *in* the environment, deviations from a natural environmental space can cause disorientation and motion sickness.[51,88] For this reason, virtual space or virtual image formats are more suitable when successful communication of the spatial information may be achieved through spatial distortions (Fig. 8). However, even in these formats the content of the environment may have to be enhanced by aids such as graticules to help the user discount unwanted aspects of the geometric distortion.[89–91]

In some environmental simulations the environment itself is the object of interest. Truly remarkable animations have been synthesized from image sequences taken by NASA spacecraft which mapped various planetary surfaces. When electronically combined with surface altitude data, the surface photography can be used to synthesize flights over the surface through positions never reached by the space-

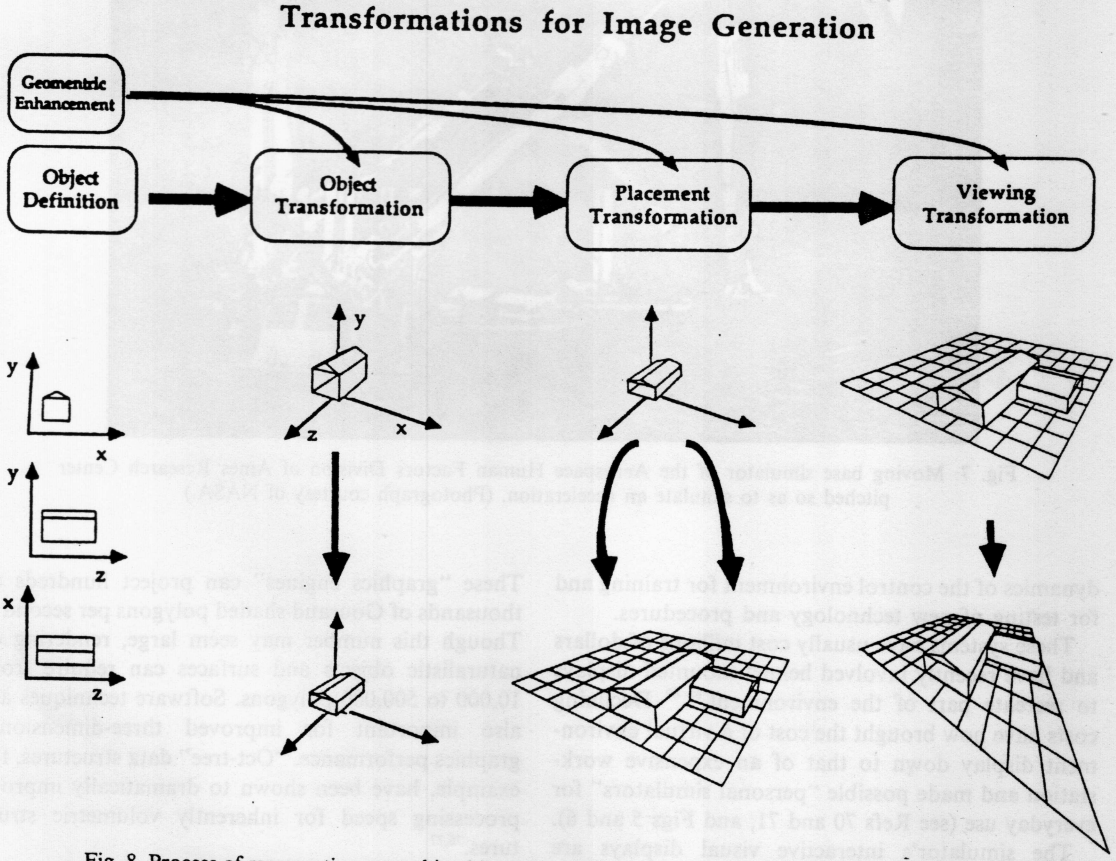


Fig. 8. Process of representing a graphic object in virtual space allows a number of different opportunities to introduce geometric distortions or enhancements. These may either be a modification of the transforming matrix during the process of object definition or they may be modifications of an element of a model. These modifications may take place: (1) in an object relative coordinate system used to define the object's shape; or (2) in an affine or even curvilinear object shape transformation; or (3) during the placement transformation that positions the transformed object in world coordinates; or (4) in the final viewing transformation. The perceptual consequences of informative distortions are different depending on where they are introduced. For example, object transformations will not impair apparent positional stability in a head-mounted display, whereas manipulations of the viewing transformation can.

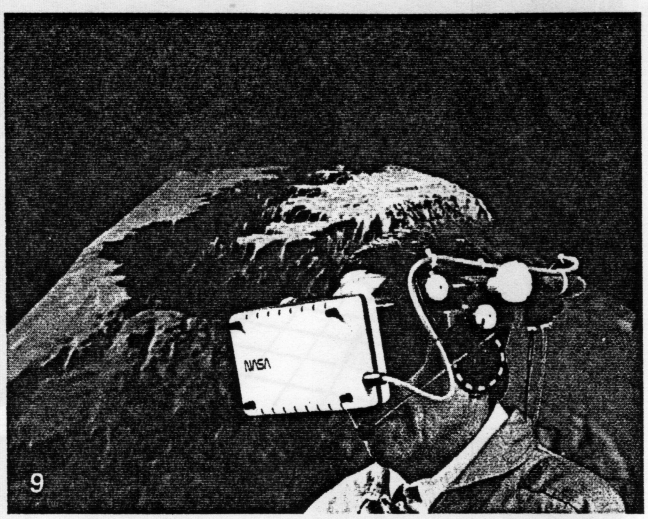


Fig. 9. When high-performance computer display technology can be matched to equally high resolution helmet display technology, planetary scientists will be able to use these systems to visualize remote environments such as the surface of Mars to plan exploration and to analyze planetary surface data. (Photograph courtesy of NASA.)

craft's camera.[92] Recent developments have made possible the use of these synthetic visualizations of planetary and Earth surfaces for interactive exploration and they promise to provide planetary scientists with the new capability of "virtual planetary exploration".[93,94] (Fig. 9).

3.3. *Physical and logical simulation*

Visualization of planetary surfaces suggests the possibility that not only the substance of the surface may be modeled but also its dynamic characteristics. Dynamic simulations for virtual environments may be developed from ordinary high-level programming languages like Pascal or C, but this usually requires considerable time for development. Interesting alternatives for this kind of simulation have been provided by simulation and modeling languages such as SLAM II, with a graphical display interface, TESS.[95] These very high languages provide tools for defining and implementing continuous or discrete dynamic models. They can facilitate construction of precise systems models.[96]

Another alternative made possible by graphical interfaces to computers is a simulation development environment in which the simulation is created through manipulation of icons representing its separate elements, such as integrators, delays, or filters, so as to connect them into a functioning *virtual machine*. A microcomputer program called "Pinball Construction Set" published in 1982 by Bill Budge is a widely distributed early example of this kind of simulation system. It allowed the user to create custom simulated pinball machines on the computer screen simply by moving icons from a tool kit into an "active region" of the display where they would become animated. A more educational, and detailed example of this kind of simulator was written as educational software by Warren Robinett. This program, called "Rocky's Boots",[97] allows users to connect icons representing logic circuits that are animated at a slow rate so the user may watch their detailed functioning. More detailed versions of this type of simulation have now been incorporated into graphical interfaces to simulation and modeling languages and are available through widely distributed systems such as the interface builder distributed with NeXt® computers.

The dynamical properties of virtual spaces and environments may also be linked to physical simulations. Prominent, noninteractive examples of this technique are James Blinn's physical animations in the video physics courses, "The Mechanical Universe" and "Beyond the Mechanical Universe."[98,99] These physically correct animations are particularly useful in providing students with subjective insights into dynamic three-dimensional phenomena such as magnetic fields. Similar educational animated visualizations have been used for courses on visual perception[100] and computer-aided design.[101] Physical simulation is more instructive, however, if it is interactive and interactive virtual spaces have been constructed which allow users to interact with nontrivial physical simulations by manipulating synthetic objects whose behavior is governed by realistic dynamics (see Refs 102 and 103; also see Figs 10 and 11).

Some unusual natural environments are difficult to work in because their inherent dynamics are unfamiliar and may be nonlinear. The immediate environment around an orbiting spacecraft is an example. When expressed in a spacecraft-relative frame of reference known as local-vertical-local-horizontal, the consequences of maneuvering thrusts becomes markedly counter-intuitive and nonlinear.[106] Consequently, a visualization tool designed to allow

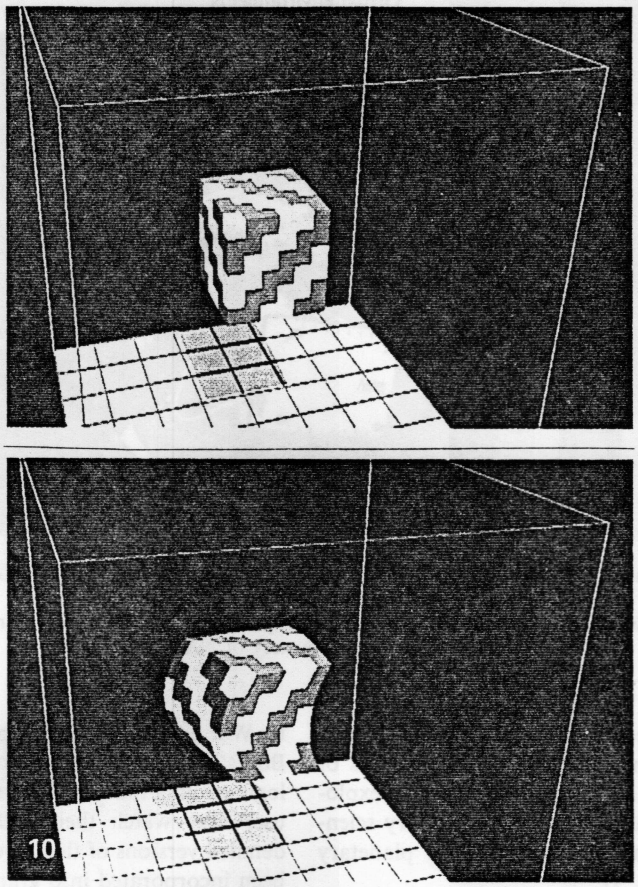


Fig. 10. Nonrigid cube is dynamically simulated to deform when a force is applied. Though computationally expensive, this kind of dynamic simulation will markedly increase the apparent realism of virtual environments. (Photograph courtesy of Andrew Witkin.)

manual planning of maneuvers in this environment has taken account of these difficulties.[107–109] This display system most directly assists planning by providing visual feedback of the consequences of the proposed plans. Its significant features enabling interactive optimization of orbital maneuvers include an "inverse dynamics" algorithm that removes control nonlinearities. Through a "geometric spread-sheet", the display creates a synthetic environment that provides the user control of thruster burns which allows *independent* solutions to otherwise coupled problems of orbital maneuvering (Figs 12 and 13.)

3.4. *Scientific and medical visualization*

Visualizing physical phenomena may be accomplished not only by constructing simulations of the phenomena but also by animating graphs and plots of the physical parameters themselves.[98,99] For example, multiple time functions of force and torque and the joints of a manipulator or limb while it is being used for a test movement (see, for example, Ref. 110).

One application for which a virtual space display has already been demonstrated in a commercial product has been in visualization of volumetric medical data.[77] These images are typically constructed from a series of two-dimensional slices of CAT, PET, or MRI images in order to allow doctors to visualize normal or abnormal anatomical structures in three dimensions. Because the different tissue types may be identified digitally, the doctors may perform an "electronic dissection" and selectively remove particular tissues. In this way truly remarkable skeletal images may be created which currently aid orthopedic and cranio-facial surgeons to plan operations (Figs 14 and 15). These volumetric data bases are also useful for shaping custom-machined prosthetic bone implants and for directing precision robotic boring devices for precise fit between implants and surrounding bone.[111] Though these static data bases have not yet been presented to doctors as full virtual environments, existing technology is adequate to develop improved virtual space techniques for interacting with them and may be able to enhance the usability of the existing displays. Related scene-generation technology can already render detailed images of this sort based on architectural drawings and can allow prospective clients to visualize walk-throughs of buildings that have not yet been constructed.[112,113]

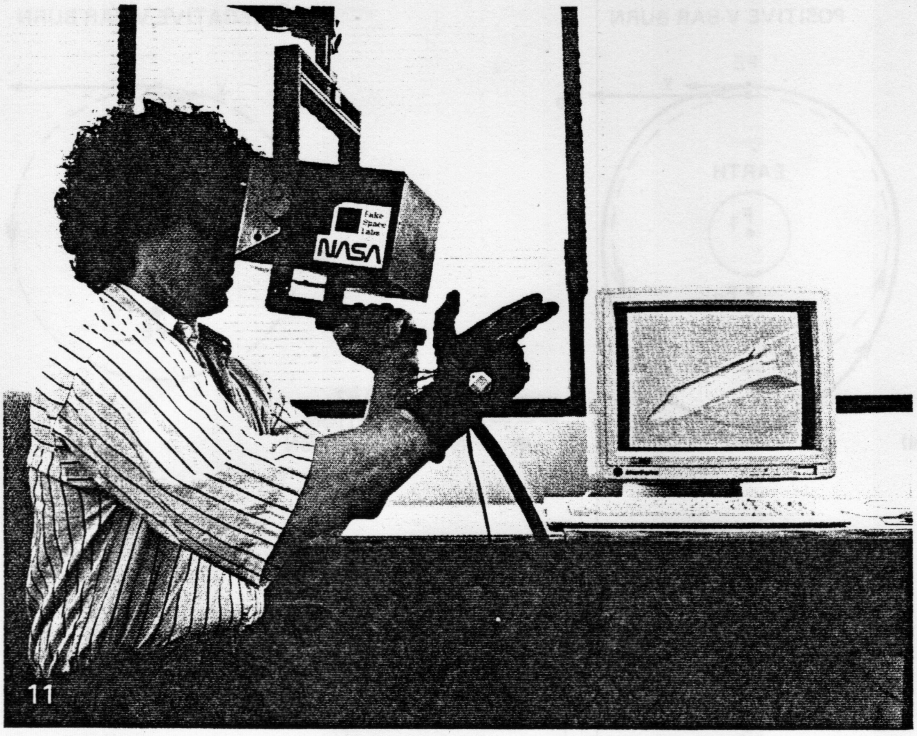


Fig. 11. Virtual environment technology may assist visualization of the results of aerodynamic simulations. Here a DataGlove is used to control the position of a "virtual" source of smoke in a wind-tunnel simulation so the operator can visualize the local pattern of air flow. In this application the operator uses a viewing device incorporating TV monitors[104] to present a stereo view of the smoke trail around the test model also shown in the desk-top display on the table.[105] (Photograph courtesy of NASA.)

3.5. *Teleoperation and telerobotics and manipulative simulation*

The second major technical influence on the development of virtual environment technology is research on teleoperation and telerobotic simulation.[19,114,115] Indeed, virtual environments have existed before the name itself as telerobotic and teleoperations simulations. The display technology, however, in these cases was usually panel-mounted rather than head-mounted (but see Ref. 116). A key difficulty was lack of a convenient and cheap head tracker. The current popular, electromagnetic, six-degree-of-freedom position tracker developed by Polhemus Navigation,[117] and also see Ref. 118 and 119, consequently, was a key technological advance. In other techniques for tracking the head position, accelerometers or optical tracking hardware may be used.[61,120]

A second key component of a teleoperation work station, or of a virtual environment, is a sensor for coupling hand position of the end-effector at a remote work site. The earlier mechanical linkages used for this coupling have been replaced by joysticks or by more complex sensors that can determine hand shape, as well as position. Modern joysticks are capable of measuring simultaneously all three rotational and three translational components of motion. Some of the joysticks are isotonic[121] and allow significant travel or rotation along the sensed axes, whereas others are isometric and sense the applied forces and torques without displacement.[122] Though the isometric sticks with no moving parts benefit from simpler construction, the user's kinematic coupling in his hand make it difficult for him to use them to apply signals in one axis without cross-couples signals in other axes. Consequently, these joysticks use switches for shutting down unwanted axes during use. Careful design of the break-out forces and detentes for different axes on the isotonic sticks allow a user to minimize cross coupling in control signals while separately controlling the different axes.[61,62]

Although the mechanical bandwidth might have been only of the order of 2–5 Hz, the early mechanical linkages used for telemanipulation provided force-feedback conveniently and passively. In modern electronically coupled systems force-feed-back or "feel" must be actively provided, usually by electric motors. Although systems providing six degrees of freedom with force-feedback on all axes are mechanically complicated, they have been constructed and used for a variety of manipulative tasks.[123,124] Interestingly, force-feedback has been particularly helpful in the molecular docking work at the University of North Carolina (see Fig. 16) in which chemists manipulate molecular models of drugs in a computer graphics physical simulation in order to find optimal orientations for binding sites on other molecules.[125]

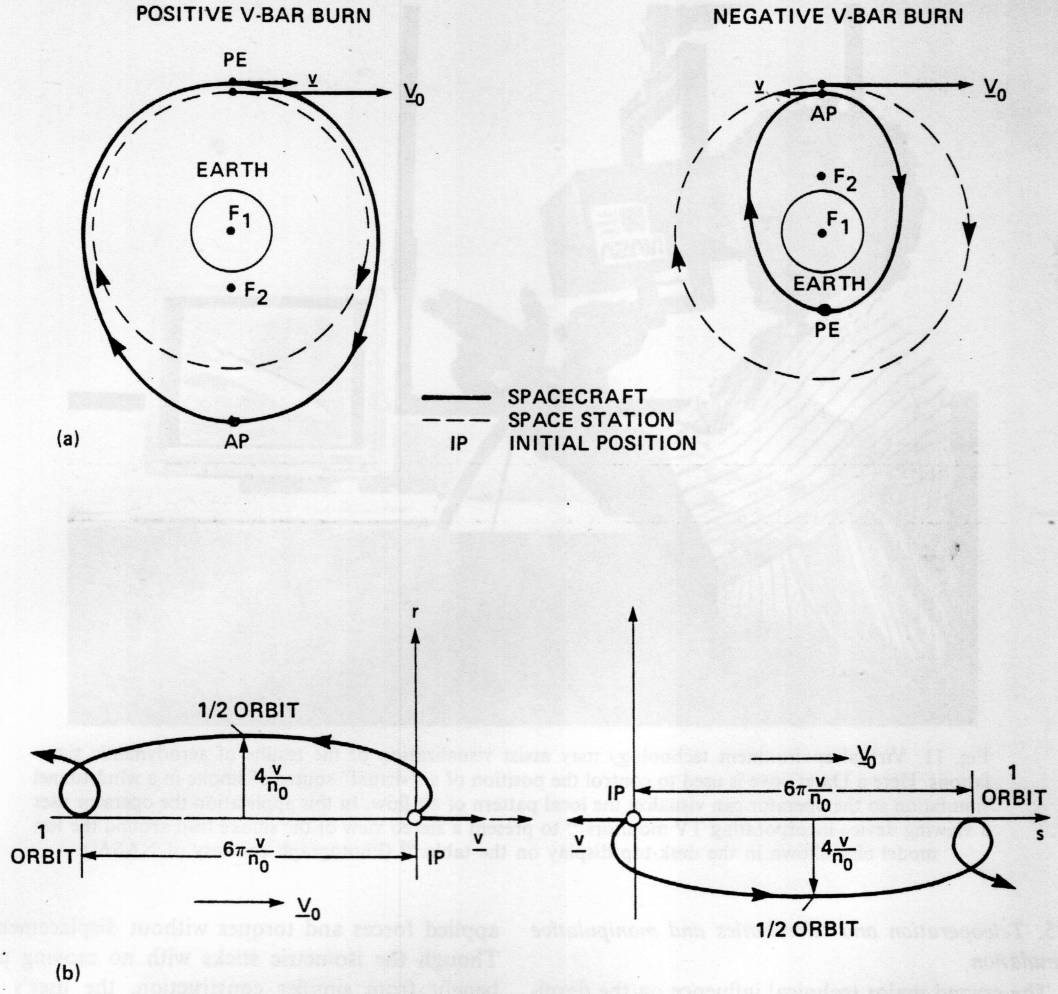


Fig. 12. Unusual environments sometimes have unusual dynamics. The orbital motion of a satellite in a low earth orbit (a) changes when thrust v is made either in the direction of orbital motion, V_o, (left) or opposed to orbital motion (right) and indicated by the change of the original orbit (dashed lines) to the new orbit (solid line). When the new trajectory is viewed in a frame of reference relative to the initial thrust point on the original orbit (Earth is down, orbital velocity is to the right; see lower panels), the consequences of the burn appear unusual. Forward thrusts (left) cause non-uniform, backward, trochoidal movement. Backward thrusts (right) cause the reverse.

High-fidelity force-feedback requires electromechanical bandwidths over 30 Hz. Most manipulators do not have this high a mechanical response. A force-reflecting joy-stick with these characteristics, however, has been designed and built (Fig. 17). Because of the required dynamic characteristics for high fidelity, it is not compact and is carefully designed to protect its operators from the strong, high-frequency forces it is capable of producing (see Refs 126–128 for some descriptions of typical manual interface specifications; and also see Ref. 129).

Manipulative interfaces may provide varying degrees of manual dexterity. Relatively crude interfaces for rate-controlled manipulators may allow experienced operators to accomplish fine manipulation tasks. Access to this level of proficiency, however, can be aided by use of position control, by more intuitive control of the interface, and by more anthropomorphic linkages on the manipulator.

An early example of a dextrous, anthropomorphic robotic end effector is the hand by Tomovic and Boni.[130] A more recent example is the Utah/MIT hand.[131] Such hand-like end effectors with large numbers of degrees of freedom may be manually controlled directly by hand-shape sensors; for example, the Exos, exoskeletal hand (see Ref. 132 and Fig. 19).

Significantly, the users of the Exos hand often turn off a number of the joints raising the possibility that there may be a limit to the number of degrees of freedom usefully incorporated into a dextrous master controller.[133] Less bulky hand shape measurement devices have also been developed using fiber optic or other sensors (Fig. 20);[134,135] however, use of these

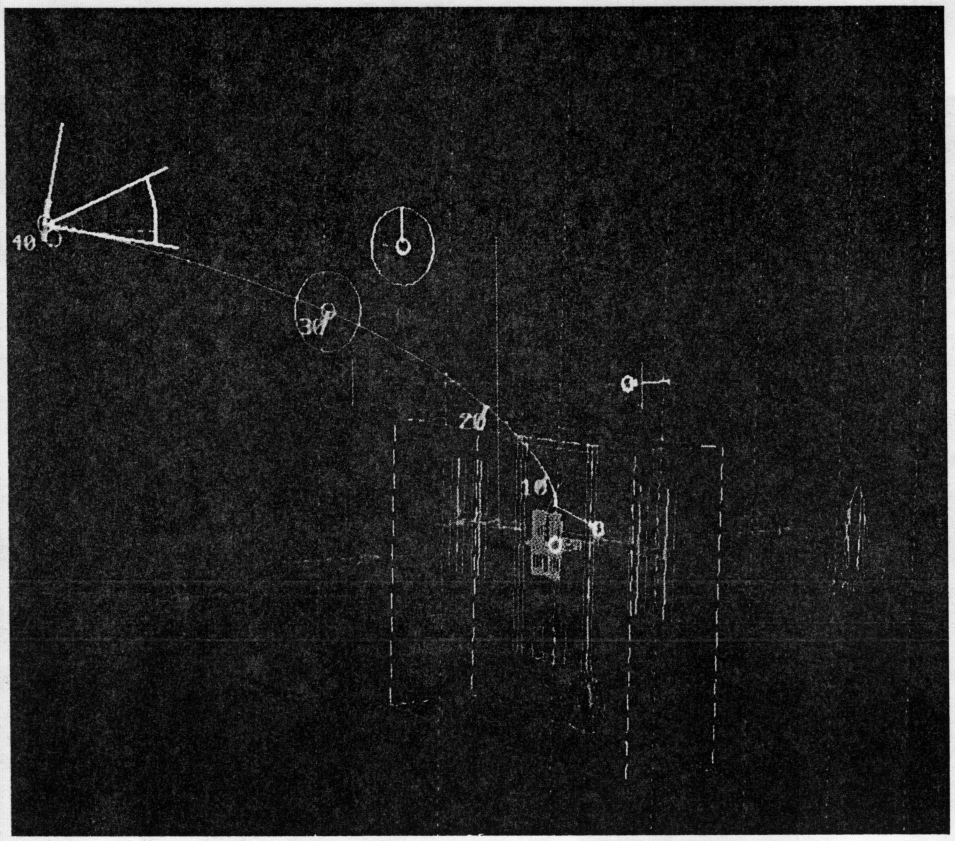


Fig. 13. Proximity operations planning display presents a virtual space that enables operators to plan orbital maneuvers despite counter-intuitive, nonlinear dynamics and operational constraints, such as plume impingement restrictions. The operator may use the display to visualize his proposed trajectories. Violations of the constraints appear as graphics objects, i.e. circles and arcs, which inform him of the nature and extent of each violation. This display provides a working example of how informed design of a planning environment's symbols, geometry, and dynamics can extend human planning capacity into new realms. (Photograph courtesy of NASA.)

alternatives involves significant trade-offs of resolution, accuracy, force-reflection and calibration stability as compared with the more bulky sensors (Figs 21–23).

3.6. *Photography, cinematography and video technology*

Since photography, cinema and television are formats for imagery that create synthetic environments, it is not surprising that technology associated with special effects for these media have been applied to virtual environments. The LEEP optics, which are commonly used in many "virtual reality" stereo-viewers, were originally developed for a stereoscopic camera system using matched camera and viewing optics to cancel the aberrations of the wide angle lens. The LEEP system field of view is approximately 110° × 55°, but it depends on how the measurement is taken.[137] Though this viewer does not allow interpupilary adjustment, its large entrance pupil (30 mm radius) removes the need for such an adjustment. The image pairs used, interestingly, are only 62 mm apart, closer together than the average interpupilary distance. This choice helpfully reduces the likelihood that users need to diverge their eyes to achieve binocular fusion.

An early development of a more complete environmental illusion through cinematic virtual space was Morton Heilig's "Sensorama". It provided a stereo, wide field-of-view, egocentric display with coordinated binaural sound, wind, and odor effects.[138] A more recent, interactive virtual space display was implemented by the MIT Architecture Machine Group in the form of a video-disk-based, interactive, map of Aspen, Colorado.[139] The interactive map provided a video display of what the user would have seen were he actually there moving through the town. Similar interactive uses of video-disk technology have been explored at the MIT Media Lab.[140] One feature that probably distinguishes the multimedia work mentioned here from the more scientific and engineering studies reported previously, is that the media artists, as users of the enabling technologies, have more interest in synthesizing highly integrated environments including sight, sound, touch and smell. A significant part of their goal is the integrated experience of a "synthetic place". On the other hand, the simulator designer is only interested in capturing the total experience insofar as this experience helps specific training and testing.

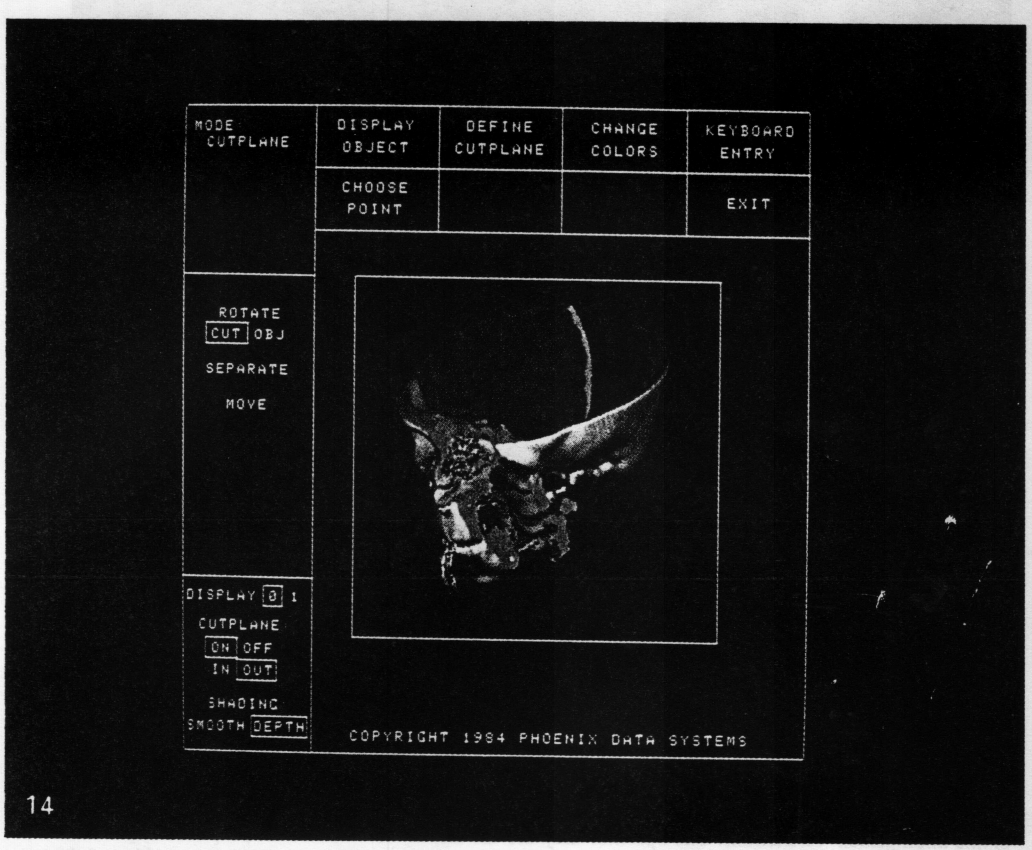


Fig. 14. Successive CAT scan X-ray images may be digitized and used to synthesize a volumetric data set which then may be electronically processed to identify specific tissue. Here bone is isolated from the rest of the data set and presents a striking image that even non-radiologists may be tempted to interpret. Forthcoming hardware will give physicians access to this type of volumetric imagery for the cost of an expensive car. (Photograph courtesy of Octree Corporation, Cupertino, California.)

3.7. *Role of engineering models*

Since the integration of the equipment necessary to synthesize a virtual environment represents such a technical challenge in itself, there is a tendency for groups working in this area to focus their attention on collecting the individual technologies. Accomplishment of specific tasks, however, places distinct performance requirements on the simulation. These requirements may be determined empirically for each task, but a more general approach is to use human performance models to help specify them. There are good general collections that can provide this background design data (e.g. Refs 141–143) and there are specific examples of how scientific engineering knowledge and computer-graphics-based visualization can be used to help designers conform to human performance constraints.[144–146] Useful sources on human sensory and motor capacities relevant to virtual environments are also available (see Refs 129, 147–151; and also Fig. 24).

Because widely available current technology limits the graphics and simulation update rate in virtual environments to less than 20 Hz, understanding the control characteristics of human movement, visual tracking, and vestibular responses is important for determining the practical limits to useful work in these environments. Theories of grasp, manual tracking,[27] spatial hearing,[148] vestibular response, and visual-vestibular correlation[88,152] all can help to determine performance guidelines.

Predictive knowledge of system performance is not only useful for matching interfaces to human capabilities, but it is also useful in developing effective displays for situations in which human operators must cope with significant time lags, for example those >250 msec, or other control difficulties. In these circumstances, accurate dynamic or kinematic models of the controlled element allow the designer to give the user control over a predictor which he may move to a desired location and which will be followed by the actual element (see Refs 15 and 18; and also Fig. 25).

Another source of guidelines is the performance and design of existing high fidelity systems themselves (see Refs 151–154; and also Figs 26 and 27). Of the virtual environment display systems, probably the one with the best visual display is the CAE Fiber Optic Helmet Mounted Display, FOHMD,[66,67] which is used in military simulators. It presents two 83.5° monocular fields of view with adjustable binocular

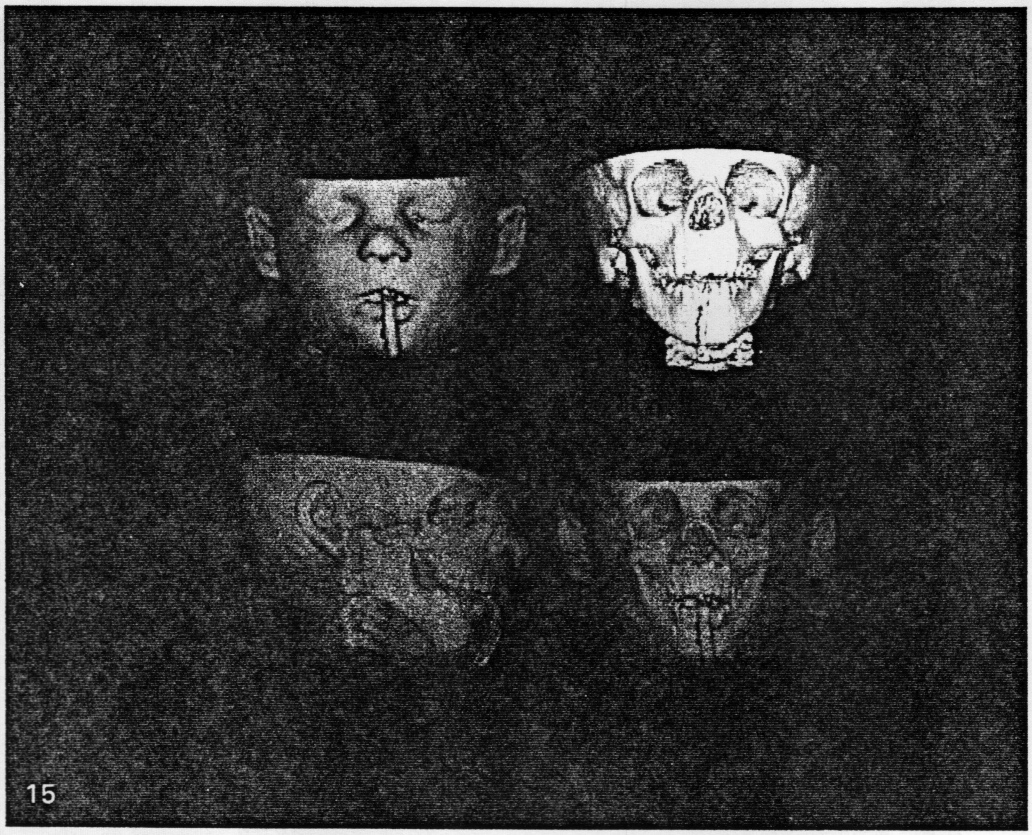


Fig. 15. Different tissues in volumetric data sets from CAT scan X-ray slices may be given arbitrary visual properties by digital processing in order to aid visualization. Here tissue surrounding the bone is made partially transparent so as to make the skin surface as well as the underlying bone of the skull clearly visible. This processing is an example of enhancement of the content of a synthetic environment. (Photograph courtesy of Octree Corporation, Cupertine California.)

overlap, typically about 38°, giving a full horizontal field-of-view up to 162°. The Wright–Patterson Air Force Base Visually Coupled Airborne Systems Simulator or VCASS display, which also presents a very wide field of view, has been used to study the consequences of field-of-view restriction on several visual tasks.[155] Their results support other reports that indicate that visual performance is influenced by increased field of view, but that this influence can become negligible at fields of view greater than 60°.[156]

A significant feature of the FOHMD is that the 60 Hz sampling of optical head position had to be augmented by signals from helmet-mounted accelerometers to perceptually stabilize the graphics imagery during head movement. Without the accelerometer signals, perceptual stability of the enveloping environment requires head-position sampling over 100 Hz, as illustrated by well calibrated teleoperations viewing systems developed in Japan.[157,158] In general, it is difficult to calibrate the head-mounted, virtual image displays used in these integrated systems. One solution is to use a see-through system, as illustrated by Hirose, and to compare the positions of real objects and superimposed computer-generated objects.[39]

Two integrated virtual environments systems for which performance and calibration data are not yet fully published are the NASA Ames Research Center's virtual interface[159] and the teleoperations interface at The National Advanced Robotics Research Centre, Salford, UK.[160] Technical descriptions and performance data for these and other virtual environment or visualization systems are likely to appear in journals cited in this paper, in this journal and in two new journals: *Presence: the Journal of Teleoperations and Virtual Environments*, MIT Press, Cambridge, Massacheucetts and *Pixel, the Magazine of Scientific Visualization*, Pixel Communications Inc., Watsonville, California.

4. VIRTUAL ENVIRONMENTS: PERFORMANCE AND TRADE-OFFS

4.1. *Performance advances*

With the state of off-shelf technology, it is unlikely that a fully implemented virtual environment display will today uniquely enable useful work at a price accessible to the average researcher. Those systems that have solved some of the major technological

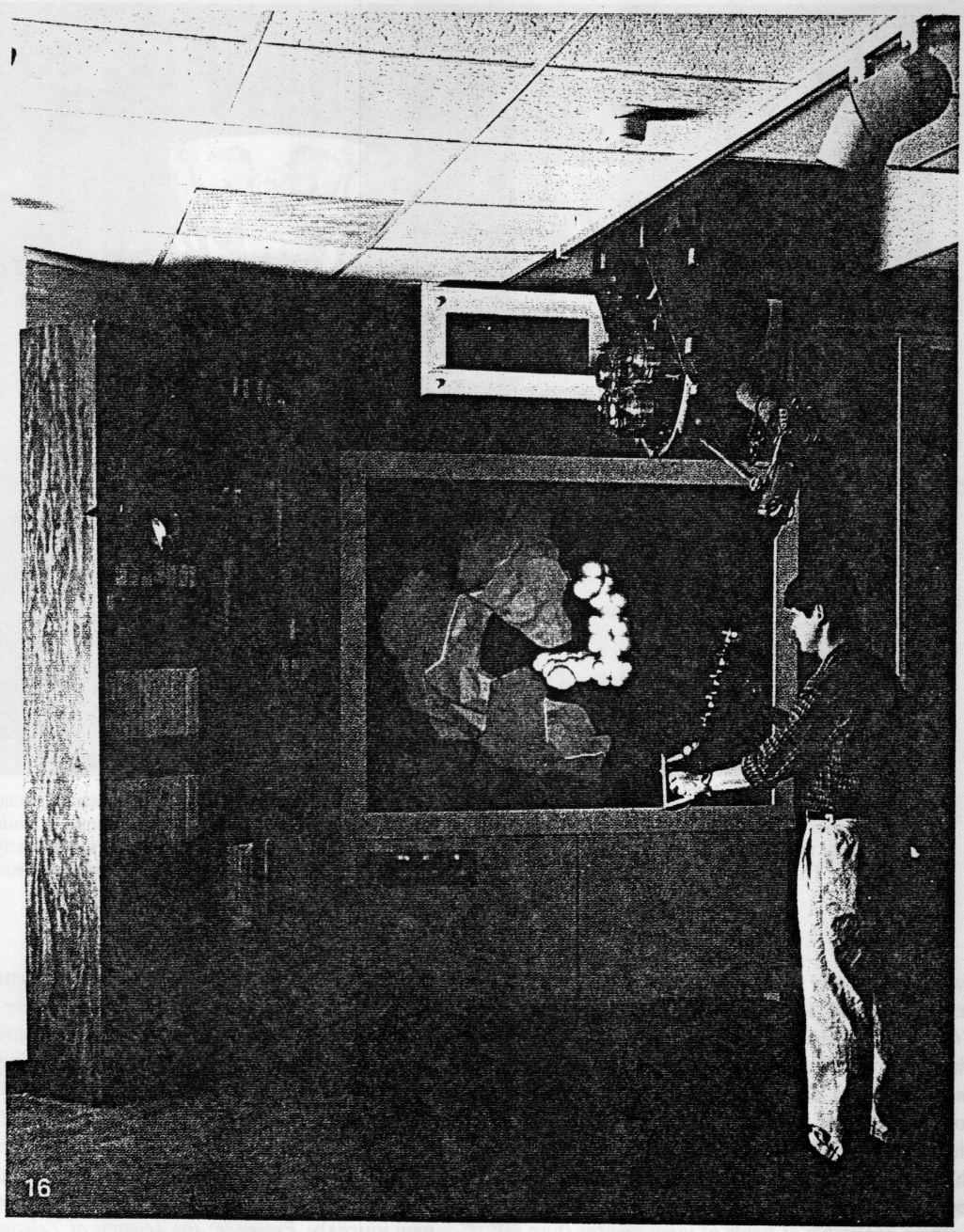


Fig. 16. Researcher at the University of North Carolina uses a multidegree-of-freedom manipulator to maneuver a computer graphics model of a drug molecule to find binding sites on a larger molecule. A dynamic simulation of the binding forces is computed in real time so the user can feel these forces through the force-reflecting manipulator and use this feel to identify the position and orientation of a binding site. (Photograph courtesy of University of North Carolina, Department of Computer Science.)

problems, that is, adequate head-tracking bandwidth, viewing resolution comparable to existing CRT technology, do so through special purpose hardware that is very expensive. The inherent cost of some enabling technologies, however, is not high and development continues, promising improved performance and flexibility (e.g. optical head tracking[120] and high quality detailed volumetric display hardware for medium cost workstations stations, see Ref. 161). However, no matter how sophisticated or cheap the display technology becomes, there will always be some costs associated with its use. With respect to practical applications, the key question is to identify those tasks that are so enabled by use of a virtual environment display, that users will choose this display format over alternatives.

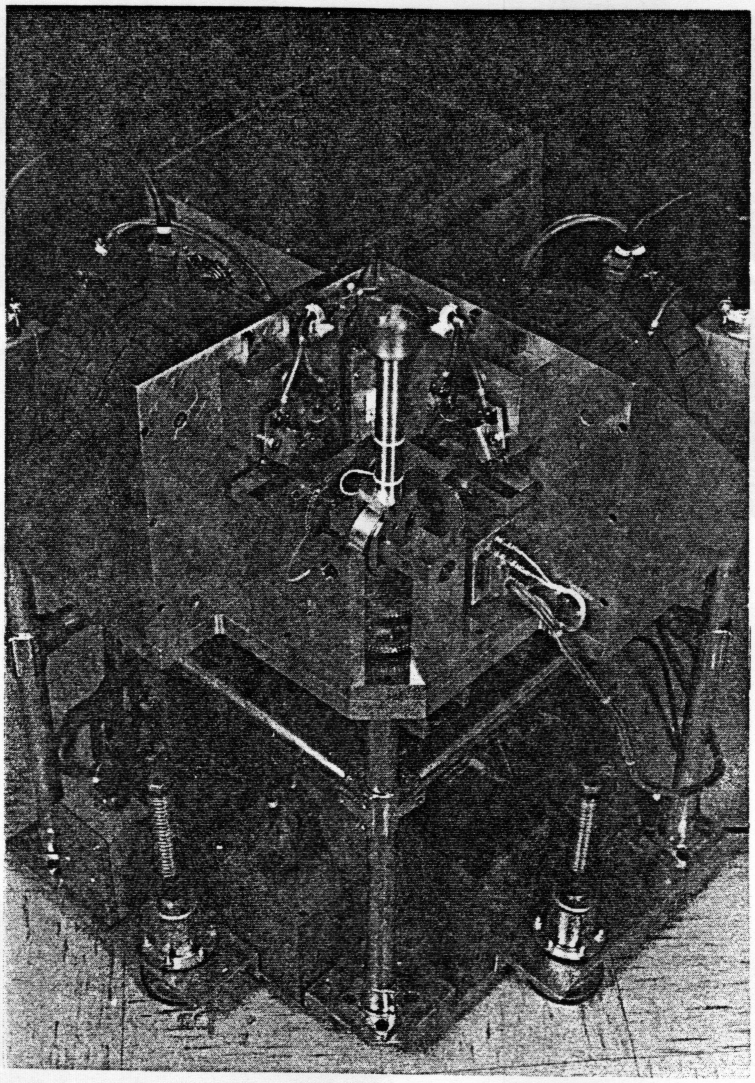


Fig. 17. A high-fidelity, force-reflecting two-axis joystick designed to study human tremor. (Photograph courtesy of B. Dov Adelstein.)

4.2. *Stereoscopic visual strain*

Designers of helmet-mounted displays for military applications have known that field use of stereoscopic displays is difficult because precise alignment is required to avoid problems with visual fatigue.[162,163] Accordingly, stereo eye strain is a likely difficulty for long-term use of stereo virtual environments. However, new devices for measuring acuity, accommodation, and eye position[164] may help improve designs. Development of a self-compensating display that adjusts to the refractive state and position of the user's eyes is one possibility. As with eye strain, the neck strain caused by the helmet's mass is likely to be relieved by technical advances such as miniaturization. But there will always be a cost associated with required use of head gear.

4.3. *Resolution/field-of-view trade-off*

Another cost associated with head-mounted displays, is that though they may generally have larger fields of view than the panel-mounted alternative, they will typically have correspondingly lower spatial resolution. Eye movement recording technology has been used to avoid this trade-off by tracking the viewer's current area of fixation so that a high-resolution graphics insert can be displayed there. This technique can relieve the graphics processor of the need to display high-resolution images in the regions of the peripheral visual field that cannot resolve it.[165] Reliable and robust eye tracking technology is still, however, costly, but fortunately may be unnecessary if a high resolution insert of approximately 30° diameter may be inserted. Since in the course of daily

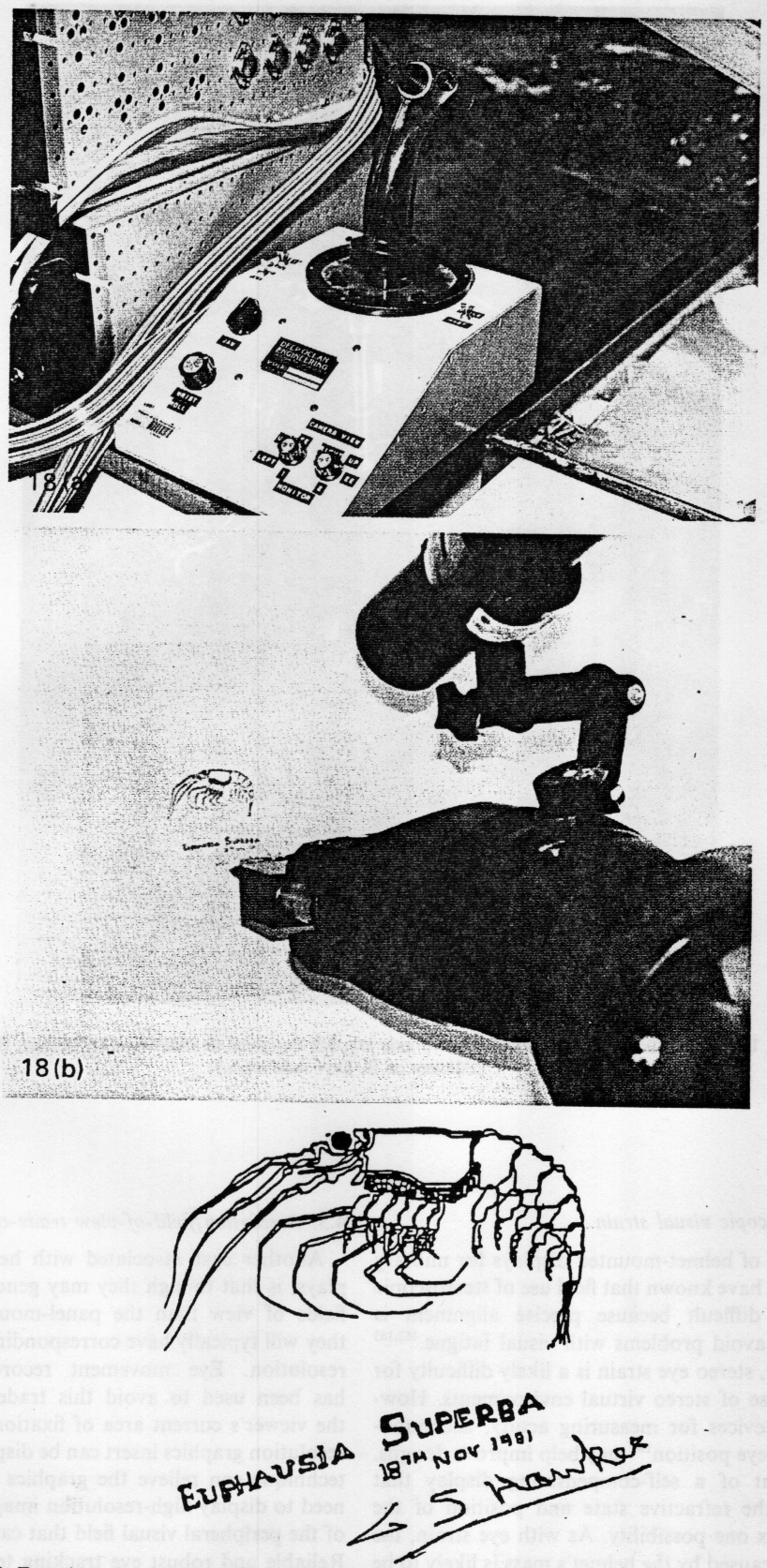


Fig. 18. Experienced operators of industrial manipulator arms (middle) can develop great dexterity (see drawing at bottom) even with ordinary two-degree-of-freedom, joystick interfaces (top) for the control of robot arms. Switches on the control box shift control to the various joints on the arm. (Photographs courtesy of Deep Ocean Engineering, San Leandro, California.)

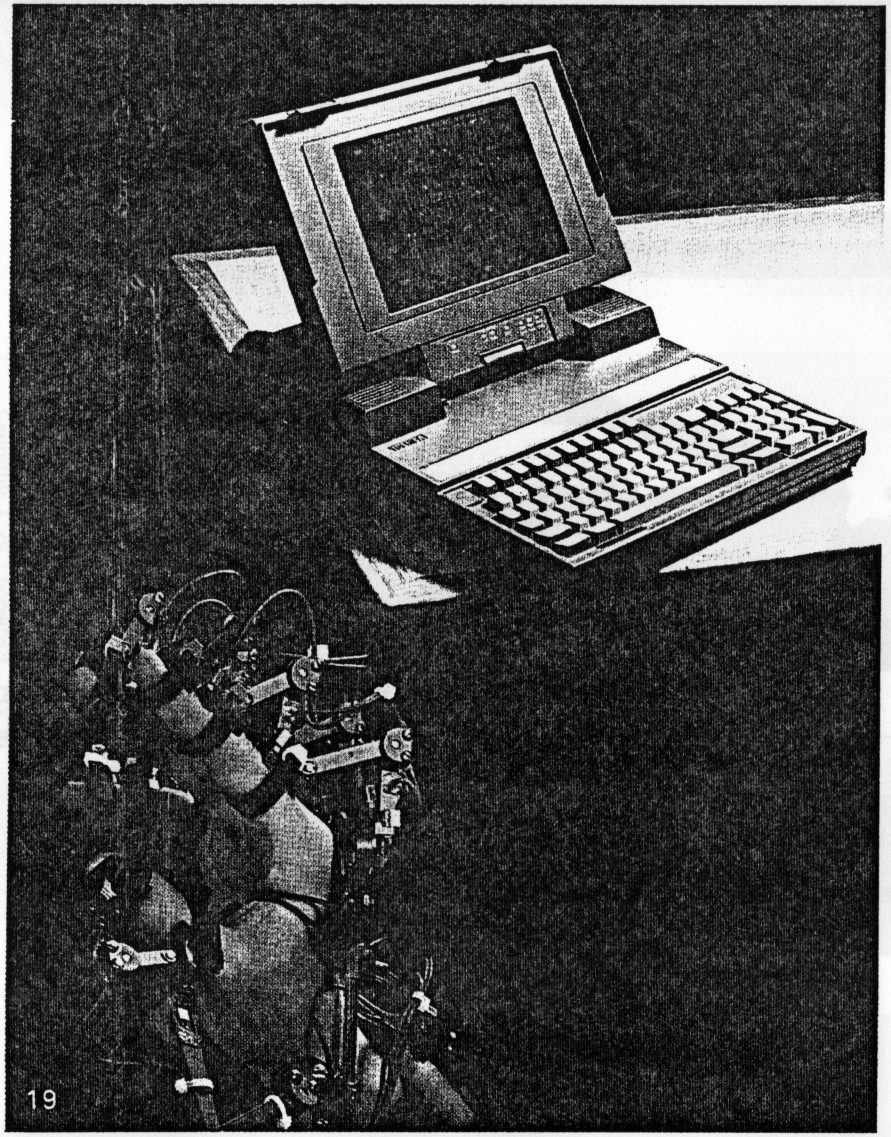
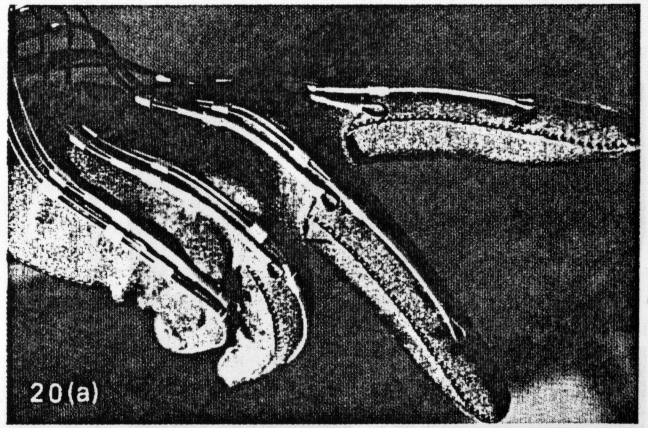


Fig. 19. An exoskeletal hand-shape measurement system in a dextrous hand master which can drive a dextrous end-effector. (Photograph courtesy of Exos Inc., Burlington, Massachausetts.)



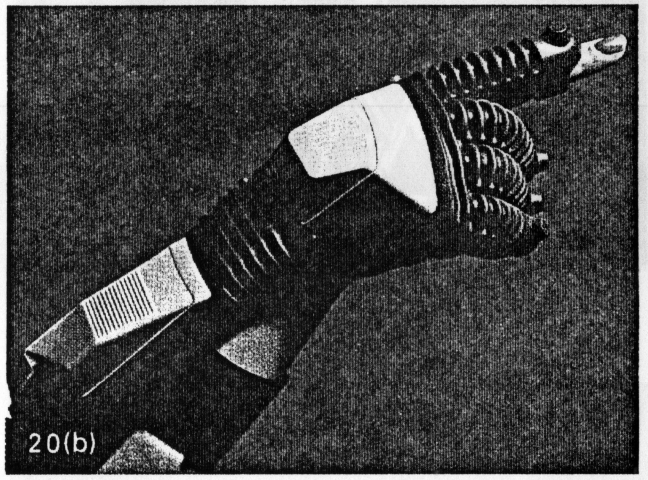


Fig. 20. Less bulky hand shape measuring instruments using flexible sensors (top panel: courtesy of VPL, Redwood City, California; bottom panel: courtesy of W. Industries, Leicester, U.K.).

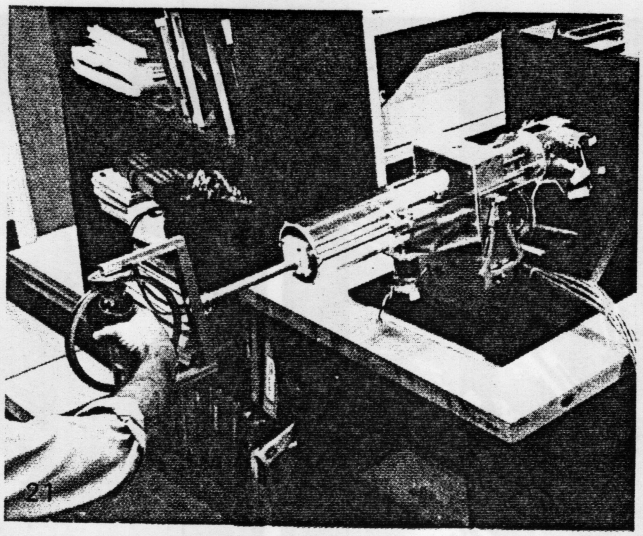


Fig. 21. A six degree of freedom force reflecting joystick.[123] (Photograph courtesy of JPL, Pasadena, California.)

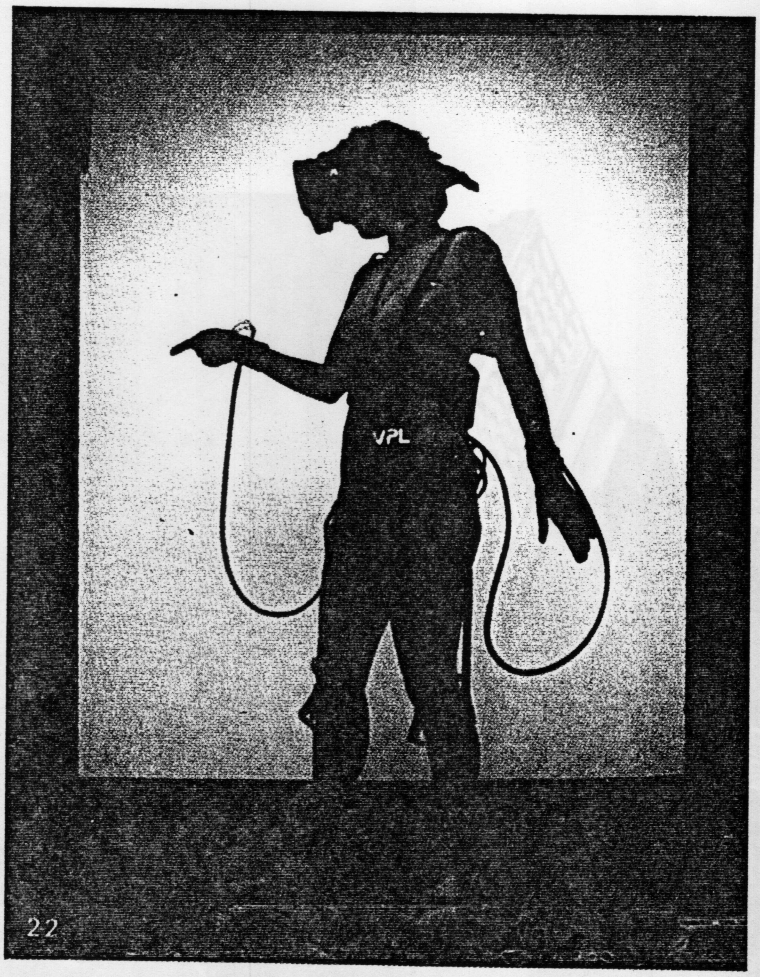


Fig. 22. Fiber-optic flexion sensors used by VPL in the DataGlove have been incorporated in a body-hugging suit. Measurements of body shape can be used to dynamically control a computer-graphics image of the body which may be seen through the head-mounted viewing device.[136] (Photograph courtesy of VPL, Redwood City, California.)

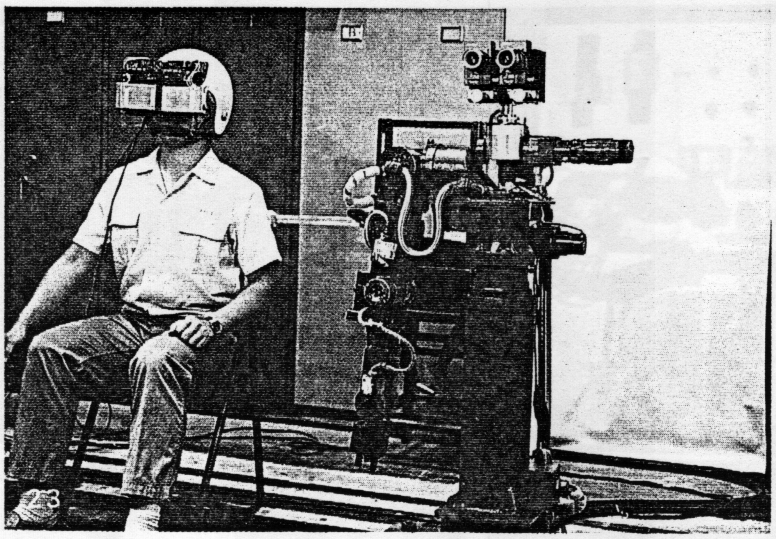


Fig. 23. Head and hand position sensors allow the user to control the head and arm position of a teleoperations robot which provides a stereo video signal that may be seen in the viewing helmet. (Photograph courtesy of Susumu Tachi.)

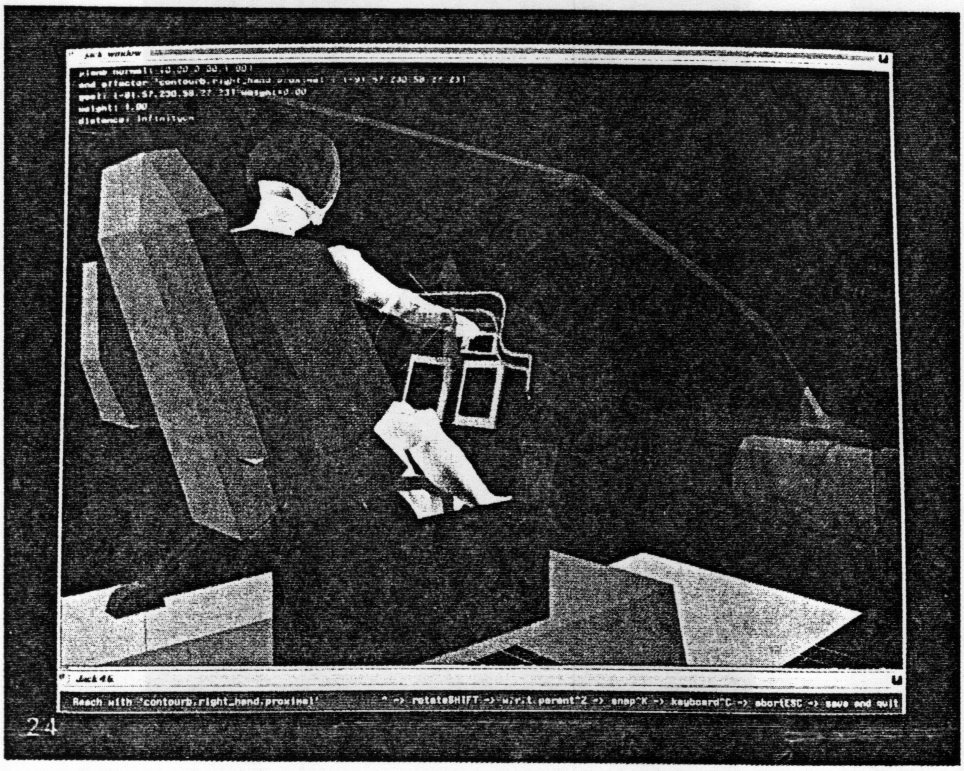


Fig. 24. "Jack" screen[145,146] example of a graphics display system that is being developed to assist cockpit designers to determine whether potential cockpit configurations would be consistent with human performance limitations such as reach envelopes or visual field characteristics. (Photograph courtesy of NASA.)

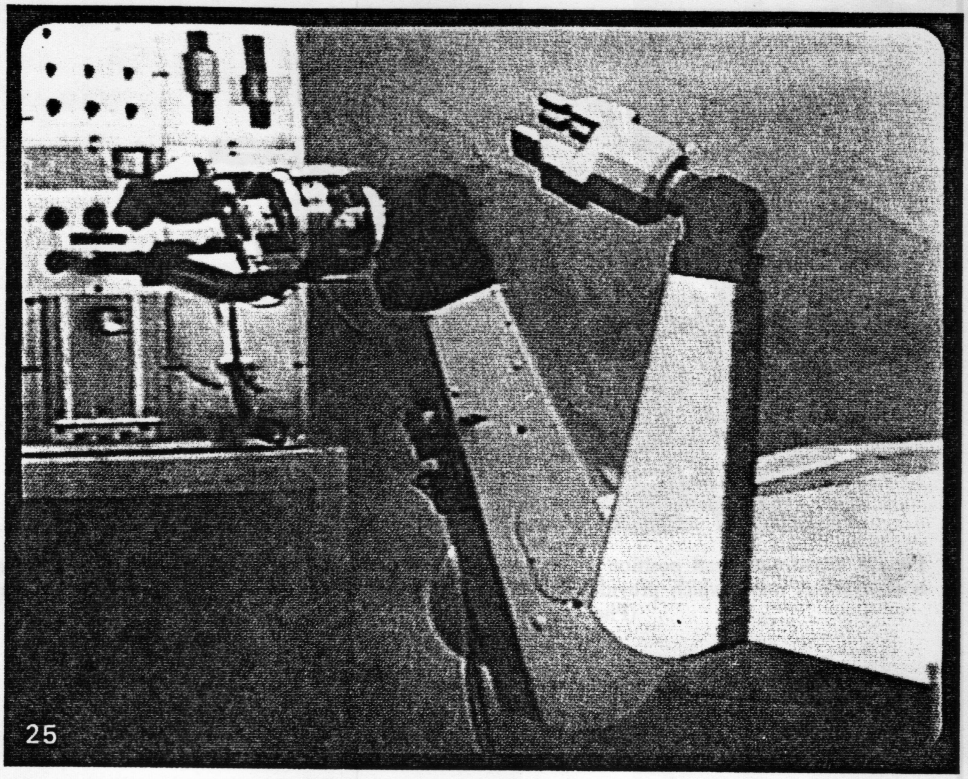


Fig. 25. Graphic model of a manipulator arm electronically superimposed on a video signal from a remote work-site to assist users who must contend with time delay in their control actions. (Photograph courtesy of JPL, Pasadena, California.)

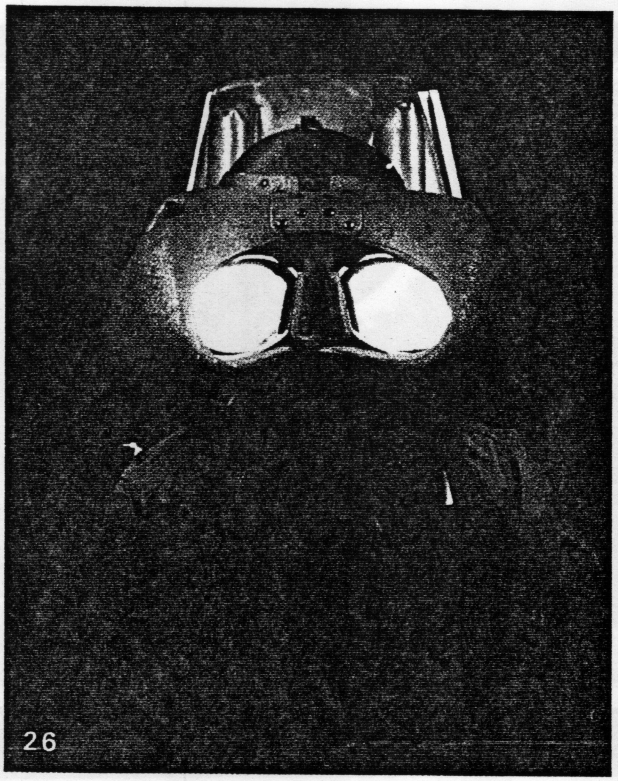


Fig. 26. Visually Coupled Airborne Systems Simulator of the Armstrong Aerospace Medical Research Laboratory of Wright-Patterson Air Force Base can present a wide field-of-view stereo display (120° × 60°) which is updated at up to 20 Hz. Head position is measured electromagnetically and may be recorded at a slower rate Visual pixel resolution 3.75 arcmin/pixel. (Photograph courtesy of AAMRL, WPAFB.)

Fig. 27. Though very expensive, the CAE Fiber Optic Helmet Mounted display, FOHUD, is probably the best head-mounted, virtual environment system. It can present an overall visual field 162° × 83.5° with 5 arcmin resolution with a high resolution inset of 24° × 18° of 1.5 arcmin resolution. It has a bright display, 30 foot-Lambert, and a fast, optical head-tracker, 60 Hz sampling, with accelerometer augmentation. (Photograph courtesy of CAE Electronics, Montreal, Canada.)

life most eye movements may be less than 15°,[166] a head-mounted display system need not employ eye tracking if the performance environment does not typically require large amplitude eye movements.

4.4. *Unique capabilities*

In view of these and certainly other costs of virtual environment displays, what unique capabilities do they enable? Since these systems amount to a communications medium, they are intrinsically applicable to practically anything—education, procedure training, teleoperation, high-level programming, exploratory data analysis, and scientific visualization.[153] One unique feature of the medium, however, is that it enables multiple, simultaneous real-time foci of control in an environment. Tasks that involve manipulation of objects in complex visual environments and also require frequent, concurrent changes in viewing position, for example, laparoscopic surgery,[167] are tasks that are naturally suited for virtual environment displays. Other tasks that may be mapped into this format are also uniquely suitable. In selecting a task for which environment displays may provide useful interfaces it is important to remember that effective communication is the goal, and that consequently one need not aspire to creating a fully implemented virtual environment; a virtual space or a virtual image might even be superior. For non-entertainment applications, the illusion of an alternative reality is not necessarily the goal of the interface design.

4.5. *Future mass markets*

It is difficult to foretell the future practical mass-market applications for virtual environments. Like three-dimensional movies, the technology could only be a transient infatuation of visionary technophiles, but the situation is more likely analogous to the introduction of the first personal computer, the Altair. At its introduction, the practical uses for which small computers like it have become essential, word processing, data bases and spreadsheets, seemed well beyond its reach. In fact, spreadsheet programs like VISICALC had not even been conceived! Accordingly, some of the ultimate mass-market applications of virtual environments are likely to be unknown today. Possibly, once the world is

densely criss-crossed with high bandwidth, public access, fiber-optic "information highways", mass demand will materialize for convenient, virtual environment displays of high resolution imagery.[168]

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VIRTUAL REALITY AND PLANETARY EXPLORATION

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Exploring planetary surface environments is central to NASA's missions and goals. A new computing technology called Virtual Reality has much to offer in support of planetary exploration. This technology augments and extends human presence within computer-generated and remote spatial environments. Historically, NASA has been a leader in many of the fundamental concepts and technologies that comprise Virtual Reality. Indeed, Ames Research Center has a central role in the development of this rapidly emerging approach to using computers. This ground breaking work has inspired researchers in academia, industry, and the military. Further, NASA's leadership in this technology has spun off new businesses, has caught the attention of the international business community, and has generated several years of positive international media coverage. In the future, Virtual Reality technology will enable greatly improved human-machine interactions for more productive planetary surface exploration. Perhaps more importantly, Virtual Reality technology will democratize the experience of planetary exploration and thereby broaden understanding of, and support for, this historic enterprise.

INTRODUCTION

Virtual Reality (VR) is a display and control technology that can surround a person in an interactive computer-generated or computer-mediated virtual environment. Using head-tracked head-mounted displays, gesture trackers, and 3D sound, it creates an artificial world of visual, proprioceptive, and auditory experience. With a digital model of an environment, it creates an artificial place to be explored, with virtual objects to be manipulated. At the extreme, every object or data point in a virtual world can be an interactive device, with each manipulated by gesture or by voice.

Ivan Sutherland created one of the pioneering Virtual Reality systems in the mid-1960's (Ref. 1), but the necessary computer graphics components were

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exceedingly primitive at the time. As a result, he and his colleagues were quickly diverted into inventing many of the fundamental algorithms, hardware, and software of computer graphics. While multi-million dollar military systems have used head-mounted displays in the years since Sutherland's work, the notion of a personal virtual environment system as a general purpose user-computer interface was generally neglected for almost twenty years.

In 1984, the author created a research program at NASA Ames Research Center to develop virtual environment workstations (Refs. 2, 3) (also known as personal simulators and Virtual Reality systems) for advanced human-computer interfaces. This technology has evolved at Ames to serve NASA's missions and goals, including planetary terrain exploration, in-space telepresence, computational fluid dynamics, and space station telerobotics. Considerable effort has been made by the author to communicate the underlying concepts and transfer the technology by giving invited technical talks at commercial firms†, delivering invited plenary speeches*, responding to very many calls and letters, and accepting numerous media interviews.

The exciting potential of this technology (variously referred to as Virtual Environment Technology, Virtual Reality, Artificial Reality, or Cyberspace) has generated a considerable amount of popular media coverage (e.g. Refs. 4-12). While some excellent articles have been written, much of the media coverage has been breathless "gee-whiz" speculation, with the more offbeat participants, applications, and pictorial illustrations dominating the scene. This, however, should not lead one to overlook the very real value of the technology, despite the strange neologisms coined to label and describe it.

To carry VR technology forward, an increasing number of academic, commercial, and government research and development efforts are appearing around the world, and new VR products (Ref. 13) continue to emerge. Even a small selection of examples illustrates the breadth of the trend. Boeing in Seattle is working with the University of Washington to demonstrate VR-based marketing and engineering design tools for the new 777 transport. In Japan,

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† For example: Hewlett Packard Research Labs, 11/87; Xerox PARC, 2/88; Lockheed Sunnyvale, 2/88; Shell Development Co., 3/88; Autodesk, 12/88; Apple Computer, 2/89.

* "The role of pictorial communication in aerospace," keynote address, NASA Symposium on Spatial Displays and Spatial Instruments, Asilomar, California, 31 August 1987.

"Personal simulators and divergence from realism," keynote address at the Symposium on User Interface Software sponsored by the Association for Computing Machinery (ACM), Special Interest Group on Computer Graphics (SIGGRAPH), Banff, Alberta, Canada, 19 Oct. 1988.

"Personal simulators and planetary exploration," keynote address at CHI '89, the annual conference on human factors in computing systems sponsored by the Association for Computing Machinery (ACM), Special Interest Group on Computer and Human Interaction (SIGCHI), Austin, Texas, 2 May 1989.

serious efforts are being devoted to the technologies of Virtual Reality, which many Japanese refer to as "Tele-existence," (stressing the communication potential). The University of North Carolina and Cornell University are independently working on virtual architectural "walk-throughs." At least one major financial organization is quietly investing in VR applications to financial transactions and markets. Several VR efforts have been funded by small business research grants from NASA and DARPA. Several Silicon Valley companies are known to be developing key VR technologies. MIT Press has just announced a new refereed journal, *Presence*, that will address Virtual Reality (and teleoperations) issues. Concerned social theorists are already holding public discussions on the potential dangers of virtual experience. High school students in Illinois are debating the merits of VR in tournaments. Many conferences on VR have been held, and are scheduled. Clearly, whether the media coverage is silly or serious, the Virtual Reality genie is out of the bottle.

Currently, a major element of the research in Virtual Reality at NASA Ames is its application to planetary surface exploration. While the amount of money being spent by NASA on this research program is vanishingly small compared with many other programs, the effort shows considerable promise. The program has received many positive comments and helpful suggestions from past members of the Mariner 9 and Viking imaging teams, and from current members of the Mars Science Working Group, the planetary rover imaging team, the Mission Analysis - System Engineering and Integration (MASE) group, and the Telepresence User Science Working Group. Other visitors (among the many) who have indicated their interest and enthusiasm include a Senate staffer and a U.S. Senator on a key budgetary committee, and Ivan Sutherland himself.

The late Hal Masursky, the photogeologist who led the Viking orbiter imaging team, and who participated in the Surveyor, Lunar Orbiter, Apollo, and Mariner missions, approved of the program's goals. Some years ago, he had been briefed on plans for the program and was very supportive in his comments. More recently he had worked with program participants to help characterize the future mission requirements.

This level of interest is very gratifying, but not entirely surprising given that for over thirty years, NASA has been developing advanced VR-related concepts and techniques for visualization and digital modeling of planetary terrain environments. Most importantly, it has been putting these concepts and techniques into practice.

OPERATIONAL EXPERIENCE IN PLANETARY TERRAIN EXPLORATION

NASA's operational experience is a valuable resource for understanding exploration behavior and user-system interface requirements. Experience in planetary surface exploration has demonstrated that the desktop workstation and the desktop metaphor are inadequate for many visualization situations.

Operational experience during the missions of Surveyor, Lunar Orbiter, Apollo, Mariner, Viking, for example, indicates that planetary explorers seek to place themselves into a natural, direct spatial relationship with planetary environments.

Visualizing the moon

The unmanned Surveyor 1 spacecraft landed on the Ocean of Storms, near the lunar equator, on June 4, 1966. Surveyor 1 was the first of five successful unmanned landings, between 1966 and 1968, designed to investigate the lunar surface environment. Each Surveyor had a video camera, and some had manipulator arms for testing the soil. To image the surface, the single video camera pointed up to a pivoting and swiveling mirror, which sampled the surrounding environment as a collection of pictures. A total of 87,632 video images were taken by the five Surveyors. Surveyor 1 took over 10,000 of them.

Technicians at the US Geological Survey pasted the images onto the interior surfaces of 34 inch spherical shells. The mosaicked panoramas imaged the entire environment surrounding the lander. These so-called Surveyor Mosaic Spheres were NASA's first virtual visual environment displays for planetary exploration.*

The Jet Propulsion Lab enlarged the Surveyor prints, and pasted them onto much larger spherical segments. When a person stood in the center of the display, he had the uncanny sense that he was on the moon. It was NASA's second virtual visual environment display for planetary exploration. In effect, NASA had obtained more than a collection of pictures of the moon. It had captured environmental images of the moon.

Preparations for manned exploration of the moon also involved both photo reconnaissance from orbit, and simulated moon walks in environments analogous to the lunar surface. Lunar explorers, both mission analysts and astronauts, generally sought to place themselves into a natural, direct spatial relationship with the environment to be explored.

The five Lunar Orbiter missions, 1966-1967, were designed to find suitable landing sites for the manned Apollo missions. The entire near side of the moon was mapped at a resolution of 60-80 meters, while selected areas were mapped at 1-5 meters. The imaging system of the Lunar Orbiters was unique.

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* When the author saw the Surveyor mosaic spheres in Life Magazine in July 1966 (Ref. 14), he immediately started making his own spherical mosaics. Though his initial efforts were relatively unrefined, he was startled at the sense of presence that could be achieved. This was what originally inspired him, and it eventually led to his creation of the Virtual Visual Environment Display -the VIVED (pronounced "vivid") system- in 1984, to his design and implementation of the Virtual Workstation at NASA Ames Research Center, and to his visualization project for planetary exploration.

70mm film was exposed and processed on orbit, and the negative was then scanned for electronic transmission back to Earth, where another negative was created. Mission analysts often found it expedient to cover large areas of the floor with enlarged and mosaicked prints representing the lunar surface. The resulting view of the surface was comparable to that of viewing part of a huge lunar globe from very close up. Clearly, desktop workstations wouldn't be much help here.

Explorers also visited real planetary environments thought to be similar to those yet to be explored. The Apollo astronauts utilized the moon-like desert craters of Nevada, for example, to prepare for their exploration of the unfamiliar lunar surface. This surrogate environment provided a first hand sense of the environment to be explored, and stimulated thinking about systems and operations for lunar exploration. Geologist Harrison Schmitt, who was project chief of lunar field geological methods at the USGS Astrogeology Branch at Flagstaff, Arizona, had been the instructor of the astronauts on such field trips to analog environments. He was later to be the only geologist to personally explore the moon, as a crewmember of Apollo 17.

During all of the Apollo missions to the moon, between 1969 and 1972, astronauts routinely took 360 degree panoramic photographs. Typical of these is a dramatic panorama taken by Eugene Cernan at the Crater Camelot during Apollo 17, the most recent manned planetary exploration mission. The panorama consists of 12 photos taken at approximately 30 degree intervals. The purpose of these panoramic images was to capture a sense of the environment for mission analysts and geoscientists. The sweeping panorama also captures the stark beauty of the rocky surface. The view scans from the glare of the sun above deeply shadowed rocks, to sharply defined boulders lit from the side, to the brilliantly illuminated landscape down-sun, and around another 180 degrees back to the glare of the sun. A desktop workstation can't do justice to such a dramatic image of the lunar terrain environment.

Visualizing Mars

Mariner missions to Mars helped prepare for the Viking lander missions by sending back the first detailed images of the surface of Mars. The only orbiter in the series was Mariner 9 in 1971-1972. On November 14, 1971, it became the first man-made object to orbit another planet. Taking more than 7100 images, Mariner 9 mapped 98% of the surface of Mars at a resolution ranging from 1 - 3 kilometers, and 1% at 100-500 meters. The Mariner 9 photos were used to construct large, flat mosaics of the surface. For example, the full extent of Valles Marineris, the spectacular 3000 mile long system of canyons named after the spacecraft that discovered it, was pieced together from a collection of orbital photos.

Of particular interest is the fact that the Mariner 9 images were also integrated to create four- and six-foot diameter spherical models of Mars. The first photo-globe was completed in September 1973, by a team at JPL. The

mosaicker was Earl Zimmerman. These globes were the first complete photomosaics of any planetary body. NASA had created the first physical model of an entire planet ever made from its images. No desktop workstation can adequately display such a globe.

During the Viking mission to Mars in 1976, the orbiters imaged the surface of Mars for over a month before landing sites were selected and certified. Over 50 thousand pictures were taken, with 90% of Mars imaged at 100-150 meters per pixel, and large areas imaged at 7-30 meters. Images of the surface were pieced together right away for a quick look at the terrain. More exact mosaicking was also done by hand. It's interesting to note that walls and tables served not only as large display surfaces for orbital imaging mosaics, they also served as group decision-making displays. Given the format and use of the mosaics, a desktop workstation would not have met the users' needs.

Desktop electronic workstations served mainly as text-oriented command, control, and communication stations. They also typically displayed the latest individual image as it was slowly built up from the transmitted bits. For example, such a console workstation was used by Jim Martin, Viking Project Manager, to observe the first color picture returned from the surface of Mars, and later, viewing another image, to verify that the pin restraining the surface sampler mechanism had indeed been worked loose.

Stereo imaging showed that apparently flat terrain was actually rolling hills and sand dunes. Because the two cameras on each lander were 82 centimeters (32.28 inches) apart, most stereo views had to be synthetically altered so that they could be fused. A tremendous computational effort went into the processing of stereo images, both for human viewing, and for stereophotogrammetric measurements of the terrain. This investment in stereo viewing is a clear indication that 3D visualization was an important part of Viking mission operations.

The Viking landers were designed to capture panoramic images of the terrain surrounding the landers that, unlike the Surveyor mosaic spheres, did not have to be awkwardly pieced together. The facsimile cameras worked brilliantly, producing many detailed panoramas subtending 342.5 degrees of azimuth by 65 degrees of elevation. By making large photographic prints of these panoramas, the mission team had a wide "picture window" into the landing site.*

When it came time to guide the sampler arm to manipulate the Martian soil, mission operations personnel resorted to the use of miniature and full-

* Recently, these digital panoramas have been displayed on the NASA Ames virtual planetary exploration system, developed by McGreevy and Hitchner, enabling the observer to be virtually surrounded by the panoramic terrain imagery, which is viewed in a head-tracked head-mounted computer display.

scale three-dimensional models. Occasionally, a lander photo of the surface would be specially processed so that the spatial relations shown were correct (to the extent possible) when the photo was laid flat next to a scale model of the lander. The model, along with such specially processed photos, helped planners to visualize the geometry of the surface sampling. The model and accompanying surface images also served as a group decision-making display, and were vitally important to the success of the mission.

One of the most interesting Viking mission snapshots shows a scientist at JPL crouched next to a full scale mockup of the lander in "the sandbox." He is holding a greatly enlarged panoramic photo. The scientist in the snapshot is trying to visualize the spatial situation from the point of view of the lander. This was so important to mission analysts that they used stereo images to pinpoint the locations and shapes of landmark rocks. They then created styrofoam models of the rocks for their full-scale model of the landing site. This is yet another example of the importance of 3D visualization in Viking mission operations. When it came to manipulating the surface, a life-sized model of the local environment, based on three-dimensional imagery, was essential. This is another situation where a personal simulator could be extremely useful for planetary exploration. While significant effort was expended to create this virtual environment for a static lander and its sampling task, the effort required to support a sampling rover will be far greater. A physical model would be too large and too elaborate, while a digital one would be ideal.

Characterizing unfamiliar terrain features

Planetary explorers have long used imaginative metaphors to characterize unfamiliar terrain features. In his book, Countries of the Mind (Ref. 15), John Middleton Murry calls poetic metaphor "the analogy by which the human mind explores the universe of quality and charts the non-measurable world." Clearly, Murry saw the link between exploration and metaphor! He further refers to metaphor as "the means by which the less familiar is assimilated to the more familiar, the unknown into the known."

This use of poetic metaphor could be seen in the exploration behavior of Mars explorers. Mariner mission personnel informally named a lacy network of canyons on Mars "the chandelier." Viking personnel referred to the moons of Mars as "potato-shaped." Rocks around the Viking landers were colloquially known by such names as "Big Joe," "the muffler," or "Mr. Badger."

Voyager mission personnel also used poetic metaphor. Prominent features on Miranda, a moon of Uranus, were initially called "the chevron", "the racetrack", and "the pancake stack." Triton, the major moon of Neptune, is said to have large areas of "canteloupe terrain."

Magellan researchers have described terrain features an Venus as looking like the clay-animation character, "Gumby," like tiles, or even spider-like.

They have described the highlands of Venus as so extensively deformed by geological forces that they are like bread dough which has been kneaded.

The heavy emphasis on food (pancakes, potatoes, canteloupe, bread) as the known quantity in the metaphorical dyad is not unique to NASA people. IBM researchers recently imaged molecules of benzene and the caption on the photograph in a science journal said that they looked like "rows of freshly baked doughnuts."

EXPLORING ENVIRONMENTS ANALOGOUS TO MARS

Scientists and engineers explore Mars-like environments in order to develop an understanding of how to explore Mars itself. It is important to realize the extent to which planetary exploration relies on the use of Mars-like terrain on Earth. Unlike digital models of Mars, which explicitly capture the specific nature of that planetary environment, analog environments serve as general models, enabling the development of concepts, theories, and systems by analogy.

Learning How to Look for Life on Mars in Antarctica

Current preparations for the exploration of Mars reveal exploration behaviors that illustrate the value of presence in terrain environments. Just as in the missions of Surveyor, Lunar Orbiter, Apollo, Mariner, and Viking, explorers still seek to put themselves into a natural spatial relationship with the environments to be explored. They also seek to use the familiar to assimilate the unfamiliar.

A Mars-like environment can be found on Earth in the dry valleys of Antarctica. These remote and inhospitable valleys are cold, rocky, and without surface vegetation or animals. But the lakes in these valleys may help in the search for evidence of ancient life on Mars. Divers who have cut tunnels through the 18 feet of surface ice, have found living mattes of blue-green algae at the bottoms of these lakes. Current conditions in the dry valleys, including the lakes, are thought to be similar to those that existed on Mars 3.5 billion years ago when these algae first appeared on Earth. Could this form of life have appeared during that period on Mars, too? Scientists are exploring Antarctica to learn how to search for ancient life on Mars. They are making Antarctica familiar in order to assimilate the unfamiliar on Mars.

Scientists who dive under the ice of the Antarctic lakes also use remotely operated vehicles, or ROVs. They use remote control not to avoid the trip to Antarctica, but to extend their reach once there. But they want a greater sense of presence in the underwater environment than they can get with current ROVs. They want the ability to collect samples just as they would if they were physically present at the sampling site. They seek telepresence interfaces to put themselves into a natural spatial relationship with the remote

environments to be explored. Further, these scientist/explorers believe that by demonstrating the utility of telepresence for real planetary science in Antarctica, they will improve the chances that the technology will be available for later application on Mars.

Current plans call for a central manned base on Mars with global access to unmanned rovers (Ref. 16). Thus, Mars explorers will use remote control not to avoid the trip to Mars, but to extend their reach once there. Just as in Antarctica, these planetary explorers will want a vivid, "first hand sense" of the remote environment. They will seek to put themselves into a natural spatial relationship with the environments to be explored. They will want the ability to collect samples just as they would if they were physically present at the sampling site.

Getting a Sense of Mars-like Terrain in Death Valley

Every year or so, a group of planetary mission analysts, designers, and geoscientists takes a field trip to personally experience Mars-like terrain in Death Valley and environs. The trip is for those who are engaged in the analysis and design of surface systems, landers, robotic imaging, and mission planning. Their objectives are revealing (Ref. 17):

1. "Get a first hand sense of natural terrain thought to be similar to candidate landing [and roving] sites on Mars"
2. "Get a first hand sense of a geological traverse in unfamiliar terrain"
3. "Stimulate thinking on safe landing and roving techniques"

The behavior of these planetary explorers demonstrates that a first hand sense of the environment to be explored is a very high priority for thinking about systems and operations for planetary exploration. These scientists and engineers wish to understand Mars as an environment by surrounding themselves with, and exploring, a similar environment.

As part of this effort, they typically compare surface views with aerial views of the Mars-like terrain. Thus, they attempt to learn to interpret orbital imagery of terrain as an environment consisting of paths and obstacles. These explorers intuitively understand that to appreciate the affordances of an environment, the environment must be experienced concretely and directly through personal experience.

Observing Geologists at Work in the Field

Since the presence of human geologists is held by some to be essential to the conduct of field geology on remote planetary surfaces (Ref. 18), a field study was recently conducted to observe and characterize the nature of that presence (Ref. 19). The study was conducted in the Mojave Desert of Southern California at the Amboy lava field, a landscape which is analogous to terrain on Mars. Two experienced planetary geologists were interviewed and observed

during the conduct of surface operations. Each subject then wore a head-mounted video camera/display system, which replaced his natural vision with video vision, while attempting to conduct further surface explorations. As a result of this study, some specific field activities of these geologists have been characterized, providing more concrete guidance for the design of telepresence and terrain visualization systems.

A major advantage of presence is the opportunity to correlate willed self-motion and position with the resulting visual imagery so as to enhance one's understanding of the spatial arrangement of the environment and its constituent objects and their components. The geologists observed in the field exhibited and described exactly such behaviors. They moved themselves relative to the environment, and moved objects relative to themselves, in order to understand the terrain. They observed the environment from orbit (ie. by studying orbital photographs), spiralled down from high altitudes in light planes to obtain dynamic oblique perspectives, climbed to high ground for a contextual view, measured terrain with their paces, accumulated mental models of the environment by visual scanning as they walked, oscillated slightly about a point in space to observe the glint of sunlight from crystals in rock faces, turned rock samples over in their hands, and judged the size of grit by "tasting" it. They observed the terrain at a wide range of scales, and from many different perspectives.

Engineering in the field

Planetary surface imaging systems are tested in Mars-like terrain, typically the desert or volcanic terrain. Recently, a team of researchers went to a site in Death Valley known as Mars Hill in order to test a new laser imaging system that is being developed for future planetary rovers. This site is strewn with rocks and boulders in a configuration comparable to that surrounding the Viking 2 lander. This provided an appropriate test of the laser system.

The laser scans the terrain in a raster, that is, a parallel set of closely spaced horizontal scans. A stepper motor drives the laser along each scan, collecting a set of distance measurements along each scan line. Taking into account the position of the laser, and the precise direction and distance at each point on the raster, a three-dimensional digital terrain model is created.

Initial results of the test produced a vividly detailed model of the terrain, clearly showing the shapes and positions of individual rocks and boulders, the overall morphology of the terrain, and very detailed views of channels formed by water erosion. Observers familiar with Mars Hill have viewed various computer-generated perspective images of the terrain, and found that the laser-captured terrain model closely resembles the morphology of the site.

DIGITAL MODELS OF PLANETARY TERRAIN

Another kind of terrain model currently used in planetary exploration is the digital model. These are created by measuring the terrain with photographs, stereophotogrammetry, laser range finders, radar altimeters, synthetic aperture radar, and other means. The advantage of digital modeling over collecting images is that the model representing the planet may itself be explored. Vistas never before seen can be generated in color, in stereo, dynamically, enabling a dramatic expansion of exploration capability. Ultimately, all of the spatially correlated information about a planet could be accessed via such a model.

Comparing orbital and surface views

If limited to orbital views of planetary terrain, planetary geologists are constrained from fully and naturally exploring the environment. To illustrate this, a Landsat satellite view of Wyoming might be compared with a surface view of Grand Teton National Park (e.g. as seen by a hiker). This would highlight the vast difference of interpretations associated with orbital views versus surface views. A satellite picture is perceived as a two-dimensional texture, not a habitat, not an environment. The surface view is the kind of view that we have evolved to perceive. It is difficult to view the satellite image and imagine the infinitude of surface views in useful detail. Yet even a static surface view is a pale shadow of the experience of presence in the environment. Without the capacity for freely moving about, one obtains a very diminished understanding of the environment.

A virtual reality interface would integrate the space in the picture with the space around the viewer, and it would enable the direct and natural exploration of the terrain. It would then be easy to interpret and interact with paths to traverse, obstacles to overcome, places too dangerous to tread, safe, sheltered areas, regions with resources, and useful or valuable objects, that is, all the affordances of the environment.

Synthetic views of the planets

Static imagery taken from the vantage point of orbit, or even from the planetary surface, cannot provide an unconstrained, interactive view of planetary environments. A solution, short of actual presence, is to create digital models of planetary terrain from the photographs and other measurements, and then to explore those models in a direct, natural, and intuitive way.

A digital terrain model can be created by taking several pictures: enough to cover an interesting area, enough to see all sides of the terrain features, enough to determine the elevations from stereophotogrammetry. That is precisely what the US Geological Survey has done since the late 1970's with some of the Viking Orbiter views of Mars. By generating digital models from

the collection of pictures, views from any point can be computed as needed. Early topographic visualization work was also done by Michael Kobrick and his colleagues at the Jet Propulsion Lab, resulting in synthetic flights over digital models of terrain derived from radar data, including Olympus Mons and Mt. Shasta, as in the films, "Topo Follies," and "Topo Follies II."

More recently, Kevin Hussey and his colleagues at JPL have digitally explored a three-dimensional digital model of the entire Los Angeles area. They used a single Landsat picture and digital elevation data from the Defense Mapping Agency. They generated over 3000 perspective images from the digital model and produced an animated virtual flight over the area. By allowing the eye to traverse the scene (albeit non-interactively), the interpretability of the terrain is distinctly enhanced. Digital models of Mars, Miranda (a moon of Uranus), and Triton (a moon of Neptune) have also been explored via animated virtual reconnaissance flights computed by Kevin's group.

The case of Miranda is particularly indicative of the power of digital modeling of the planets. Even though the Voyager spacecraft only had time to snap a handful of photographs of Miranda as it sped past, animation† based on digital modeling makes it possible to virtually helicopter over the surface, flying low over the mountains, peering down into canyons. This kind of capability represents nothing short of a revolution in exploration.

Currently, the Magellan spacecraft is digitizing the surface of Venus using synthetic aperture radar and a radar altimeter. The temperatures, pressures, and dense atmosphere of Venus do not reward actual presence of exploring humans or their machines. Thus, virtual exploration is the only practical way to explore that hostile planet. During the 243 day primary mission that began on August 10, 1990, Magellan will map 70-90% of the surface at a resolution of approximately 300 meters, about two tenths of a mile.* The mission will generate a trillion bytes of terrain data, more data than all previous planetary exploration missions combined.

Magellan data is providing a detailed digital model of Venus for virtual exploration on Earth. Already, dramatic virtual flights of exploration over the fascinatingly varied terrains of Venus have been computed. In the future, supercomputer-based visualization systems will allow scientists and engineers to directly and naturally explore Venus as they would explore any other

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† An even greater effect of presence can be achieved with interactive viewing while virtually surrounded by the environment. Recent virtual reality work by McGreevy and Hitchner at NASA Ames has demonstrated a variety of means for generating a sense of virtual presence in complex planetary terrain models.

* This resolution is vastly superior to that of the Pioneer Venus mission of 1978-1980. Pioneer's resolution was 50 thousand meters, about 31 miles, per pixel!

environment of interest, not as an animated movie, but as an interactive virtual environment.

Comprehensive planetary models

In future terrain exploration missions, system operators, scientists, and crewmembers will be able to access highly integrated digital models of the planets and moons as explorations progress. These environmental models will incorporate many spatially correlated varieties of planetary data, including geomorphology, resource distribution, traversibility, atmospheric conditions, and habitability. NASA's Mission to Planet Earth, for example, will generate an unprecedented amount of such data for managing diminishing resources and tracking environmental concerns.

For manned exploration of Mars, environmental models are already under development. Tom Duxbury, a leading planetary cartographer, estimates that selected potential exploration sites will need to be modelled at a resolution of twenty centimeters per pixel. He also stresses that comprehensive three dimensional digital models will be needed to support future terrain exploration missions (Ref. 20). Based on the exploration behavior observed during previous manned and unmanned missions, and in analog environments, it is certain that users will seek to put themselves into natural spatial relationships with these integrated environmental models. This will allow users to readily interpret inherent relations in the environmental data. It will give users a natural, coherent framework for mastering the potentially overwhelming tidal wave of fine-grained, multi-dimensional, multi-planetary information. Beyond this utilitarian payoff, bringing the planets virtually down to Earth will democratize space exploration.

DESIGNING EXPLORATION WORKSTATIONS

The activities of the people who participate in planetary exploration might collectively be called their exploration behaviors. The preceding overview of NASA's operational experience in planetary exploration, the use of analog environments, and the creation of digital terrain models highlights a wealth of exploration behaviors. It would be useful to distill these behaviors and to apply them to the design of user interfaces for exploration systems.

Limitations of the Desktop Metaphor

The desktop workstation is generally considered to be the starting point of user-computer interface design, and most current human-computer interface research emphasizes the desktop metaphor. In this view, computing is thought to be comparable to paperwork, and the objects and functions available to the user reflect this emphasis. Point-and-click interaction with icons and windows is supportive of operations performed on text and simple pictures, but this approach alone is quite inadequate for planetary exploration.

NASA's experience in planetary exploration has demonstrated that the desktop workstation and the desktop metaphor are inadequate for many visualization situations. Operational experience during the missions of Surveyor, Lunar Orbiter, Apollo, Mariner, Viking, Voyager, and Magellan demonstrates that planetary explorers seek to place themselves into a natural, direct spatial relationship with planetary environments.

Exploration of Mars-analog environments indicates that the behaviors of planetary explorers are not even remotely like doing paperwork. Instead, the important behaviors are locomotion throughout the environment, manipulation of objects in the environment, perception of shapes and spatial relationships, and a considerable amount of situational cognition to guide the explorations.

Digital terrain modelling techniques, which have evolved dramatically during the last thirty or so years of planetary exploration, are making it possible to virtually recreate planetary environments from the accumulated terrain data. The desktop workstation, even with so-called "multi-media," will be sorely inadequate for exploring these digital worlds.

The Exploration Metaphor

Alternative user interfaces and metaphors are needed for planetary exploration and other interactions with complex spatial environments. These interfaces and metaphors would enable the user to directly explore environments and naturally manipulate objects in those environments. Personal simulators, virtual workstations, virtual reality systems, and telepresence user interfaces are systems capable of providing this integration of user space and virtual or remote task space.

The Exploration Metaphor (Ref. 21), based on a distillation of observed exploration behaviors, is useful for guiding the look and feel of these interfaces. To apply the Exploration Metaphor is to assert that computing is like exploration, and to support objects, operations, and contexts comparable to those encountered in the exploration of natural environments. The Exploration Metaphor is a user interface style that accommodates and augments exploration behaviors. In particular, it provides a sense of presence in the terrain environment to be explored. It will thus contribute significantly to the look and feel of personal simulators, virtual reality systems, telepresence devices, and virtual workstations, in applications where complex spatial environments, real or virtual, are visualized, explored, and manipulated. Accordingly, the design of planetary exploration workstations should be based on the Exploration Metaphor.

Presence in real environments

The relationships between an ecological (or natural) environment and its inhabitants are central to James J. Gibson's theory of visual perception. This theory is probably best elaborated in his book, The Ecological Approach to Visual Perception (Ref. 22). Gibson, one of the greatest perceptual psychologists, argued that the study of vision must go beyond the study of the eye and brain. He wrote, "One sees the environment not with the eyes but with the eyes-in-the-head-on-the-body-resting-on-the-ground." He further observed, "When no constraints are put on the visual system, we look around, walk up to something interesting and move around it so as to see it from all sides, and go from one vista to another. That is natural vision..."

To be truly effective, to accommodate all aspects of natural vision, the comprehensive visual interface must provide a sense of presence, that is, it must enable the user to directly and naturally observe and manipulate objects and explore environments. That is why the combination of the head–mounted display and the hand-mounted controller provides a compellingly realistic interface to a simulated environment.

Since the visual system involves, according to Gibson, the entire body and its relationship to the environment and the objects in it, then the user's self image is also part of visual perception. Gibson wrote that the visual world is perceived, "...by an exploring visual system, and the awareness of the observer's own body in the world is a part of the experience." Gibson further emphasized this point when he wrote, "To perceive the world is to co-perceive oneself."

Gibson hypothesized that by observing one's own capacity for visual, manipulative, and locomotor interaction with environments and objects, one perceives the meanings and the utility of environments and objects. That is the gist of his theory of affordances. It follows, then, that the ways that the user is allowed to interact with virtual things in a computer-generated world will determine how well he or she can understand them. Thus, it is important to understand the kinds of interactions offered by real environments and the real objects in those environments.

What do natural environments afford the observer? Environments afford exploration. Environments are composed of openings, paths, steps, and shallow slopes, which afford locomotion. Environments also consist of: obstacles, which afford collision and possible injury; brinks or cliffs, which afford falling-off and possible injury; water, fire, and wind, which afford life and danger; and shelters, which afford protection from hostile elements. Most importantly, environments afford a context for interaction with a collection of objects.

What do natural objects afford the observer? Objects afford grasping, throwing, portability, containment, and sitting-upon. Objects afford shaping,

molding, manufacture; stacking, piling, and building. Some objects afford eating. Some very special objects afford use as tools, or spontaneous action and interaction (that is, some objects are other animals).

Clearly, natural objects and environments offer far more opportunity for use, interaction, manipulation, and exploration than the ones typically generated on computer systems. Also, a user's natural capacity for visual, manipulative, and locomotor interaction with real environments and objects is far more informative than the typically restricted interactions with computer-generated scenes. Although a virtual world may usefully differ from the real world, virtual objects and environments must provide some measure of the affordances of the objects and environments depicted, in order to more fully support natural vision.

Presence in Virtual Environments

Connecting the user's space and the virtual display space is essential for creating a sense of presence in a virtual reality. Several strategies can be used which support this linkage by building a model of the user into the simulation system. Typically, however, the observer is hardly modelled at all, other than as a pin-hole camera, the simplest model of the eye. Still, even the minimal pinhole camera model of the user can be used as a spatial link between the user and the depicted scene. At the very least, the center of projection should be located at the eyepoint of the user. This is rarely done, however, even though linear perspective, the geometric theory which describes the nature of pinhole lens imagery, was specifically designed to link the observer to the pictorial space. Differences between the geometry of a perspective image and the geometry of the user's view of that image, can have a pronounced effect on spatial perception by creating a mismatch between the user's space and the virtual display space (Ref. 23).

Various means of providing different perspective images to each eye of an observer enable the creation of stereo imagery. This adds the important cue of binocular disparity for improved spatial realism. Stereo provides an additional link between the scene and the observer by modelling the observer more completely, that is, as a pair of pinhole cameras.

In natural vision, static perspectives are rare. Moving the pinhole camera model of the observer through a computer-generated scene adds a number of spatial cues, including flow fields and the dynamic covering and uncovering of distant objects by near ones. Generally, however, this motion is presented to a passive and motionless observer on a display subtending a narrow visual angle. As a result, a sense of presence in the depicted scene is rarely achieved.

The dynamic visual effects which result from a user's actual self-motion provides a linkage between the user's space and the depicted space. This is accomplished by tracking the motions of the user, and altering the imagery accordingly. By tracking head position and orientation, for example, a

computer screen becomes more like a window. Moving closer to the screen provides a wider aperture of view. Moving left and right provides motion parallax proportional to self-motion.

A head-mounted display, with image geometry computed according to head position and orientation, enables the user to be virtually surrounded by a pictorial environment, and to move relative to depicted objects in a natural manner. By tracking hand-mounted controllers, the objects may be directly manipulated. This kind of interactive display was pioneered by Ivan Sutherland in the 60's, although the field of view of his system was a narrow 40 degrees. By stimulating more of the peripheral visual field, the sense of presence in the depicted scene can be enhanced. Thus, wide field-of-view head-mounted displays, like the original virtual reality display developed at NASA Ames, can further increase the visual sense of presence.

Implementation of a typical virtual reality system

A virtual reality system (or virtual workstation, or personal simulator) consists of the means to immerse a user in a virtual interactive environment created from digital models. Such a system is an integrated collection of body-ported input/output devices, computer and video hardware, and software to orchestrate the simulation. The user wears a head-mounted viewer. Typical viewers consist of a pair of video display screens (with their support electronics) and wide-angle magnifying lenses. The viewer is usually supported by a box of electronics for power supply, signal conversions, and functional adjustments and accessories. The viewer is generally designed so as to replace the visual field of the user, while some versions allow the imagery to be combined with the real visual environment of the user. Some researchers believe that eye-movement tracking is important, while others do not. The head-mounted unit generally carries a microphone, earphones, and a head-position and orientation sensor. Typically, the hands are fitted with shape, position, and orientation sensors. Ultimately, the entire body could be tracked, and otherwise instrumented.

A host computer integrates the (sometimes various) computing resources, the peripheral units, and coordinates their interaction. A computer graphics system generates three-dimensional scenes for display in the viewer. The imagery is altered in accordance with the head-movements of the user to provide, to the extent possible, a stable visual environment. Remote video cameras can be slaved to the motions of the user's head, providing a remote source of imagery for visual telepresence. Key peripheral systems convert voice commands to computer commands, convert computer output to synthetic speech or other sounds, and convert body movements to computer input. Hand gestures are interpreted as desired for alteration of the appearance of the scene, behavior of objects, or other interactions with the environment. Telerobotic systems can be controlled by the motions of the user's hands, providing remote manipulation. Force feedback can be used to allow synthetic or remote objects to feel more solid and real.

Digital models of various task environments, such as the Space Shuttle, Space Station, and planetary terrain, are created and stored in databases. They are displayed and manipulated by the software programs under control of the user wearing the virtual workstation. Video recorders can record what the user sees and hears for non-interactive replay later. Network links can enable a system to communicate with remote computing resources, remote task environments, and remote virtual reality systems.

THE NASA AMES VIRTUAL PLANETARY EXPLORATION SYSTEM

A Virtual Planetary Exploration (VPE) System has been developed at NASA Ames by the author and Dr. Lewis Hitchner of the Research Institute for Advanced Computer Science (RIACS). The system is a research tool for developing and testing concepts, methods, and user-based interaction strategies that may prove useful for the design of planetary exploration workstations based on the virtual reality paradigm and the Exploration Metaphor. The effort is modestly funded by the Office of Aeronautical and Exploration Technology (OAET) at NASA Headquarters.

The approach has been to:

1. review mission operational experience, mission constraints and opportunities, the state of the art in exploration technology, and future mission requirements;
2. conduct field studies in analog terrain environments;
3. work closely with the planetary exploration community;
4. characterize user exploration behaviors and requirements;
5. enlist interdisciplinary expertise to develop, implement, demonstrate, and evaluate advanced exploration workstation testbeds;
6. place special emphasis on strategies for dealing with the inherent conflicts between the high degree of interactivity associated with the virtual reality paradigm, and the extreme complexity of planetary terrain environments.

Operational applications may ultimately include support for landing site selection and certification, as well as surface operations, including: manned base construction and operation, manned and unmanned rover traversal planning and operations, and teleoperations between manned bases and remote unmanned rovers. Other potential applications include: scientific data analysis, agency advocacy of planetary terrain exploration, and public affairs.

Demonstration capability

While our emphasis is on research rather than demonstrations, these capabilities serve to communicate some of our ideas to visitors.

For example, the system is currently capable of presenting the Viking 2 lander digital mosaics in such a way that the observer has a sense of presence at the landing site. By wearing a head-tracked head-mounted display that

presents computer-controlled imagery, the observer seems to be standing on the surface of Mars at the Viking 2 lander site. The lander panorama seems to surround the observer, providing an experience comparable to that obtained with the (physical) Surveyor mosaic spheres of the 1960's. By using a feature called "virtual pixel maps," the surrounding panorama, which is very detailed, right down to tiny pebbles, can be presented without computational lag. In essence, the observer is surrounded by a virtual cylindrical image.*

The system can also compute arbitrary panoramic images from digital terrain models. Thus, the observer can virtually stand on the floor of Valles Marineris, or anywhere else on Mars, and can freely scan the entire 360 degree horizon, as well as look up to the peaks, or down to the nearby surface. The resolution of these computed panoramas is only limited by the resolution of the terrain data. Given the Mars Hill data, which has 10 centimeter resolution, the computed panorama can still be scanned at will, without rendering lag. The capability to compute a panorama from anywhere on or near the planet makes this technique far more flexible than the Surveyor mosaic spheres, which could only present the scene from the point of view of the lander.

The use of the virtual cylindrical image technique provides a sense of being in a very realistic (and hence very complex) environment without the virtual reality system becoming compute bound. In most virtual reality systems, a mere few hundred polygons can unacceptably slow down the response to head movements because the scene must be computed on-the-fly over and over again. The panoramic frame buffer technique enables the system to precompute a 360 degree panorama of any complexity, taking whatever amount of time is necessary, and then to present this image to the user without additional computation.

This technique represents one of the many engineering tradeoffs being investigated that will allow the use of virtual reality techniques with exquisitely complex environments. In this case, the user is constrained from translating about in the virtual environment, but may rotate his head to any azimuth or elevation angle. The effect is comparable to sitting in a swivel chair in ones office. The surrounding scene can very complex and realistic despite the lack of translation. A collection of spherical or cylindrical images could be computed for key sites. We have come to call this approach the "Mars National Park" metaphor, because of its correspondence with a national park's collection of scenic overlooks, between which one must attend to driving rather than sight-seeing.

Another technique for dealing with the conflict between complexity and interactivity frees the user to translate or rotate in the virtual terrain

* A spherical image would be ideal, but it would be rather more difficult to use the virtual pixel maps.

environment by restricting the complexity of the scene during rapid motions. Thus, the terrain essentially is reduced to a "cartoon Mars" when the user moves about. Whenever the user chooses to pause for a closer look, the level of terrain detail displayed is increased. Currently, the complexity is reduced by a "dumb" algorithm of subsampling the digital terrain model. Unfortunately, the cartoon Mars is sometimes so simplified that landmarks become unrecognizable. To deal with this, an effort is underway to compute "caricatures" of the terrain which retain the essential features (ie. those that are essential to a particular user) with a very small amount of terrain data. This will allow a reduction of complexity without losing the ability to navigate through the environment.

The VPE system is also capable of texture mapping a digital imaging model onto a digital terrain elevation model. In the case of Mars, the three dimensional terrain dataset was derived from Viking orbiter images, and so the resolution of the shape data is less than that of the imaging data. The now standard technique of overlaying the image data on the shape data provides the appearance of a very detailed 3D scene with less complexity. The user can freely travel about in a virtual environment created from this data, using the "cartoon Mars" approach to drastically reduce the complexity of the shape data when his is moving, and increasing the resolution when stopping for a closer look. The image data aids the user when navigating in the "low res mode."

Tentative plans call for networking to supercomputers to enable the rapid computation of a complete, photorealistic panorama whenever the user calls for one. The user would navigate through a caricature of Mars, then, upon reaching a particularly interesting location, he could call for a complete spherical environmental image. Scenic detail might appear by progressive refinement, first filling in detail at the places toward which the user is looking. The result would be a vivid sense of visual presence, with relative freedom to translate within the environment.

User-based modes of virtual planetary exploration

Current demonstration capabilities and other generic interactions serve as the building blocks of user-based interaction modes to be derived from experienced planetary explorers. For example, a recent study of exploration behavior in the field (Ref. 19) revealed that planetary geologists routinely carry out intermediate altitude aerial reconnaissance. According to one subject:

> "Doing this kind of field work, it's fairly common for us to start in the laboratory by looking at the available remote sensing data. And not just conventional air photos like this, but any other kind of data we can get, as well. And then going into the field, doing a reconnaissance of the field as a whole. And then overflying it. We commonly will rent small planes to fly over the area. It gives you a perspective that you can't get any other way. The air photos are not adequate. There are things that

the eye can detect that remote sensing cannot. There are relationships that we can see from that low altitude perspective that you can't get, either on the ground or from orbit, let's say. And so that intermediate altitude aerial reconnaissance is an important part of the kind of field work that we do."

The subject was asked to elaborate on the utility of overflight in a small plane.

"It's difficult to describe, certainly in a quantitative sense, what one does on an aerial reconnaissance. It's the perspective of geometric relationships of different units that you can't appreciate when you're standing right on the surface. You don't have that overview. It's also because you're there. You're seeing it in color. You're seeing it with your own eyes. And from an oblique perspective. And from many different perspectives, because the plane can fly around and give you whatever geometry you want, to see the areas that you're interested in."

In addition to gathering such information on the behavior of terrain explorers, we are also investigating the manipulative behavior associated with sampling outcrops during geological field work. As digital models of terrain progress to human scale detail, manipulative capability will be incorporated into the virtual planetary exploration system, particularly to support user-based telepresence research.

By working with experienced planetary explorers, their exploration behaviors can be observed, characterized, and supported by the VPE system. Then, the system can be exercised by these explorers and their colleagues in realistic mission-oriented tasks. During these exercises, we will conduct investigations regarding the specific sources of productivity or interpretation error, the nature and degree of presence and its utility, and the benefit of virtual reality techniques to specific tasks that support planetary terrain exploration.

CONCLUSION

Many of the fundamental concepts and techniques of Virtual Reality technology have been developed over 30 years by NASA as a natural part of planetary exploration missions, and VR is now being recognized as a major new paradigm in user-computer interactions. NASA is currently conducting research to apply this technology to areas that have unique payoff to support its missions and goals, which are among the most technically challenging VR applications. Planetary terrain exploration in particular will benefit from this research. Furthermore, Virtual Reality technology has the potential to democratize the experience of planetary exploration, which could have a profound effect on public perceptions of the U.S. space program.

The spinoff of VR technology is already creating new commercial opportunities, and it will greatly influence art, architecture, computer-aided design, communications, entertainment, education, medicine, scientific visualization, and many other fields. Besides highly spatial applications, it will have an impact on applications which can be cast into a spatial context (e.g. three dimensional libraries of text or other "dataspaces"). Further, it may be feasible to create virtual, dynamic three-dimensional worlds from inherently non-spatial data so as to ease interpretation and interaction. In general, Virtual Reality technology will dramatically alter human perception of the information environment.

Jacob Bronowski wrote in chapter one of his book, The Ascent of Man (Ref. 24), "Among the multitude of animals which scamper, fly, burrow, and swim around us, man is the only one who is not locked into his environment. His imagination, his reason, his emotional subtlety and toughness, make it possible for him not to accept the environment but to change it. And that series of inventions by which man from age to age has remade his environment is a different kind of evolution."

The personal simulator, an advanced user-computer interface, is one of the most recent of these inventions. When more fully developed, such devices will be able to generate synthetic perceptual environments that may be so compellingly realistic as to be worthy to be called Virtual Realities. The ability to capture and generate environments at will has the potential to provide vastly improved methods for exploring the Earth, the other planets, and synthetic worlds of our own making. Virtual Reality technology will thus provide another upward step along the exploratory path that Bronowski calls "The Ascent of Man."

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The creation of NASA's "Virtual Reality" program

In 1984, Dr. Michael W. McGreevy created the Virtual Environment Workstation (aka "Virtual Reality") program at NASA Ames Research Center in California's Silicon Valley. He wrote and distributed a description of the Virtual Workstation concept and its implementation that year, citing key applications and design details, for use in communicating his idea to division researchers and managers. He designed the Virtual Visual Environment Display (VIVED, pronounced "vivid") system configuration and guided its implementation, providing a low-cost, wide field of view, stereo head-mounted display. **He designed and implemented NASA's first Virtual Environment Workstation** (described in detail below). After creating the program conceptually, and implementing the first systems, he went to Washington and successfully advocated programmatic support for the project, and obtained sustained, expanded funding for the program. Upon his return from Washington, he has applied his knowledge of NASA's missions and goals to develop three new programs for developing and utilizing Virtual Workstation technology for Space Station Freedom, planetary exploration, and Computational Fluid Dynamics.

McGreevy's 1984 report defines the Virtual Workstation as consisting of virtual displays and controls, and outlines several applications:

> "Virtual displays and controls are devices which are not fixed in position, size or orientation because they are projected into the visual space of the user instead of physically built into a workstation...By using the entire visual space of the operator, virtual devices can incorporate the most effective strategies for information transfer. These may include more efficient use of central and peripheral vision, flexible format sizes, meta-cursors to highlight related information on multiple [virtual] screens, and dynamic allocation of virtual display space. Position and orientation sensors could be attached to the body at strategic locations to activate controls and displays, and otherwise interact with the workstation."

> "Applications to display research:
> > evaluate virtual controls and displays
> > simulate potential workstations
> > study visual telepresence displays
> > evaluate a range of limited fields of view vs. performance
> > simulate visual disorientation as in weightlessness
> > study iconic interaction with computer systems."

> "Simulation of physical workstations will also be possible...prior to actually building them."

> "In remotely controlled vehicles, such as orbiting teleoperators...[u]sing the display system, the controller would be able to direct the gaze of the remote imaging system by head position. This frees the hands for operation of the manipulators and also provides a better spatial orientation to the task environment."

> "...Since the Ames display will be able to provide a range of fields of view to one or both eyes, and either similar or different scenes to the two eyes, it will be possible to study the human factors of helmet-mounted displays in general."

> "Space adaptation syndrome [may be studied] ...on orbit... [and] ...on earth..."

> "The Ames display will allow researchers to take the concept of iconic [Macintosh-like] interaction with computer systems to its ultimate limit."

Based on the report, McGreevy obtained a small amount of seed money from division management to build a prototype display system. He designed the display system configuration, specifying the engineering tradeoffs necessary to make it both functional and affordable. He sought the help of contractors Jim Humphries, Saim Eriskin, and Joe Deardon to implement the electronics and packaging of his design, and worked closely with them to decide the appropriate tradeoffs at the circuit and module level. Together, this group built the viewer system that McGreevy dubbed VIVED (pronounced "vivid"), the Virtual Visual Environment Display. The group quickly developed a wide-angle, multiplexed stereo videotape capability and gave several demonstrations. Videotapes were made of walking from the human factors lab, through the offices of the division, and on to the hanger for a tour including the XV-15 Tilt-Rotor aircraft, and observation of its mechanics at work. When the user viewed the videos through the VIVED system, a sense of personal experience and participation were obtained.

At the same time, McGreevy integrated the hardware and developed the software, along with Amy Wu, his support programmer, to create NASA's first Virtual Workstation. Ken Uhland and Steffan Jeffers wrote the device driver for the Polhemus tracking system. The Virtual Workstation consisted of an Evans and Sutherland Picture System 2 computer graphics system with two 19" display monitors, a DEC PDP-11/40 host computer, a Polhemus head and hand tracker, and the custom-designed head-mounted display (VIVED) with its support electronics. The graphics system generated wide-angle pinhole perspective images on each of the two E&S monitors to produce stereo images. Two video cameras with fish-eye lenses were mounted on custom-built, adjustable platforms attached to the display monitors, providing the necessary image predistortion,

as well as the conversion to video. The system displayed computer-generated imagery which seemed to surround the user. The first digital database was from a study McGreevy had done of perspective displays of air traffic for the cockpit. Users felt as if they were standing on a horizontal computer-generated grid that stretched to the horizon, and they could walk among and inspect aircraft in flight. Many demonstrations were given to visitors from industry, academia, and the military, and all were very impressed with how compellingly real the virtual environment seemed to be. Particularly since the head-mounted display had cost only two thousand dollars of the ten thousand dollar budget. (The VIVED system in use today is a direct descendent of the original VIVED system. The resolution, the electronics, the packaging, and the head-mounting hardware have been improved by Jim Humphries and Dr. Morokawa, but the underlying design has not changed.)

After creating the program technically, McGreevy went to Washington D.C. to learn to advocate programs at the Agency level. In July 1985, after the Virtual Workstation program had been underway for more than a year, and the above described system had been built and demonstrated, McGreevy went to NASA Headquarters on a one year training assignment. There he served as Program Manager for NASA's entire Space Human Factors research program. As it turns out, he was asked to stay for a second year to manage Space and Aeronautical Human Factors research and Aeronautical Computer Science research.

In Washington, McGreevy was responsible for advocating and supporting the Virtual Workstation program that he had created. He had to demonstrate to upper management, to the Office of Management and Budget, and to the Congressional committees, and others how his program supported NASA's missions and goals. (While in Washington, he coined the term "personal simulator" to characterize a class of advanced user interfaces which immerse the user in an interactive, synthetic, spatial environment, that is, an artificial reality, or a computer-mediated reality.) McGreevy made presentations and wrote advocacy materials on the Virtual Workstation for presentation to NASA's advisory committees, Congress, the Office of Management and Budget, and the President. He personally convinced NASA management, beginning with the division level at Ames in 1984, all the way to top NASA managers in Washington, to provide the funding for every year of the program. Thus, not only did he personally create the project technically, he also created it administratively and fiscally.

As an example of his success in communicating the benefits of the Virtual Workstation to NASA management, McGreevy's advocacy briefing at NASA HQS in October 1987 was characterized by Dr. Mel Montemerlo, Manager of Automation and Robotics, in a NASAmail message to Dr. Dave Nagel, Chief, Aerospace Human Factors Research Division, dated 10/30/87:

> "Mike just gave a GMSR on the Virtual Workstation. There has never been a GMSR presentation like that, and there may never be again. The audience was more than impressed: they were moved.
>
> It was Human Factors' finest hour here at Code R. This is not a joke. This is not an overstatement. The only thing I regret is that Ray Colladay was not there. I wish he would have been there to see the audience reaction.
>
> Mike did good."

Mr. Scott Fisher, a media technologist, was hired by NASA over a year after McGreevy's project was underway, and he began to work on the Virtual Workstation program when McGreevy went to Washington in mid-1985. At that time, Fisher began to use McGreevy's lab, his equipment, and the functioning Virtual Workstation described above. During the time McGreevy was in Washington, Warren Robinett wrote outstanding demonstration software. Doug Kerr wrote many software tools. Jim Humphries and his crew continued to refine the viewer design. Mr. Fisher brought the VPL Dataglove to the system and conducted many demonstrations. Dr. Beth Wenzel began to conduct research in 3D sound.

By the time McGreevy returned to Virtual Workstation research at Ames in the summer of 1987, he had been able to substantially increase the visibility of, and support for, the research. Since that time, he has created and directed the Space Station head-mounted display project and the Virtual Planetary Exploration program. He also initiated the creation of the Computational Fluid Dynamics project. He conducts Virtual Workstation research, and has developed the Exploration Metaphor, field studies of the exploration behavior of planetary geoscientists, and advanced Virtual Workstations. As a result, Virtual Workstation R&D is beginning to make significant contributions to NASA's missions and goals.